

High Efficiency Audio Amplifier

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Abstract

This project combines the advantages of high efficiency of power electronics with the existing high fidelity of audio amplifiers. The result will be functionally equivalent to existing amplifiers but will use considerably less energy. A complete system was designed, simulated, built and tested in a period of three quarters. The end result is an amplifier that functions, but would not be suitable for commercial marketing. Suggestions to improve the performance are provided.

Introduction

A typical home audio setup usually uses a standalone amplifier with the sole purpose of accepting an audio source and playing that signal through speakers. The basic operation of traditional amplifiers consists of two DC voltage sources, from which the amplified signal is “carved” from. This approach isn’t very efficient as it causes amplifiers to produce excess heat, which must then be dissipated requiring large metal heatsinks, or fans in drastic situations. Amplifiers also need large transformers and capacitors to regulate and store energy which adds significant cost due to their large size[1].

Newer approaches to amplifier design are able to do away with many of the inefficiencies that have plagued older designs. These include increasing efficiency, which reduces excess heat eliminating large heatsinks. Newer designs are able to function with much smaller transformers and capacitors thus reducing a large portion of the total cost. The main disadvantage of the newer approaches is added complexity which can take a much longer time to design which is cost prohibitive to many companies[2],[3].

I will build a high efficiency audio amplifier which will operate just as well as a typical amplifier, but will not require large heatsinks or transformers and will not produce excessive heat. The benefit of this project will be an amplifier that is more sustainable to build and operate. The consumer would be able to easily replace existing less efficient amplifiers and enjoy the same sound while using less power.

This project will be to design and build a high efficiency audio amplifier, which will be used to amplify an audio signal and play it through a pair of speakers. When efficiency is mentioned in this project it is meant as the overall efficiency because both the audio amplifier and its power supply will be consuming power. A typical amplifier's efficiency is usually never mentioned, but if it is the overall efficiency is rarely mentioned since both the power supply and amplifier are inefficient.

This amplifier will also be similar to other amplifiers in terms of audio quality and versatility. Most amplifiers are able to produce music with very little distortion. This is one of the shortcomings of newer, efficient designs so careful attention to sound quality will be made. In terms of versatility, typical amplifiers are compatible with almost any pair of speakers currently available, so it is important for this project to be able to do as well[4].

Since this amplifier will use new designs, the end product will be more manageable than typical amplifiers in terms of weight and size. It is also important to keep the amplifier easy to work with because, regardless of the advantages, if the user finds it difficult to use, they will be less likely to use it.

The main features of this amplifier that allow it to perform efficiently are the full bridge inverter, the flyback DC-DC converter, and the power supply. The full requirements and specifications are shown in the tables on the next page. Each specification is supported by various marketing and engineering requirements.

Background

Audio Amplifier

An audio amplifier works as an interface between a source and a load. Most sources of audio are not capable of substantial voltage or current and cannot be directly connected to a low impedance speaker. The amplifier's job is to take the audio source as an input signal, amplify the voltage by a fixed amount and supply enough current to power a low impedance speaker. The conventional method is to use transistors like variable resistors between the speaker and a pair of DC rails so that the output signal is “carved” out. This presents substantial power losses because the same current is flowing through the transistors and the load so the voltage that transistors absorb is converted to power losses. The newer approach is to use a half bridge or full bridge inverter which minimize losses by only conducting fully on or off[5].

AC to DC power supply

Almost all small appliances are designed to operate off of mains electricity that is found in homes. Since amplifiers and their associated circuitry require DC voltage the AC power needs to be converted to DC. Most homes in the United States have a 240Vac service that is split into two 120Vac rails with respect to a grounded neutral. The AC to DC converter must be able to convert the 120Vac into a stable DC rail. Almost all commercial power supplies are manufactured to be universal, meaning that they can operate on both 120Vac or 240Vac which is the standard in other countries. This is slightly more demanding in design so the power supply was only designed to operate safely off of 120Vac.

Full Bridge Inverter

A full bridge inverter, also known as an H-bridge, consists of four transistors configured as shown in Figure 1 which allows a single DC source to apply current in two directions to an attached load. The two conduction modes for an H-bridge are shown in Figure 2 and 3. The alternative is to use a half-bridge which removes two of the switches connecting one end of the load to ground. The switches are then hooked up to a positive and negative rail so that current can be applied in both directions to the load. The H-bridge is particularly useful because a single 20V rail can apply 40Vpp to the load allowing more power out of fewer rails. The advantages of using a full bridge are reduced power supply design since only one voltage rail is required to deliver alternating current to a load. Another advantage is that even order distortion is eliminated since it is canceled out[6]. The disadvantage is that the amount of switches required is doubled and each require their own gate driving circuitry. Another drawback is that the load doesn't have a connection to ground, which can be an issue if multiple loads are intended to be powered with a shared ground. In amplifiers it is common for the ground terminal on the output of each channel to be at ground potential, so care must be taken that the consumer doesn't accidentally short the two channels together.[7]

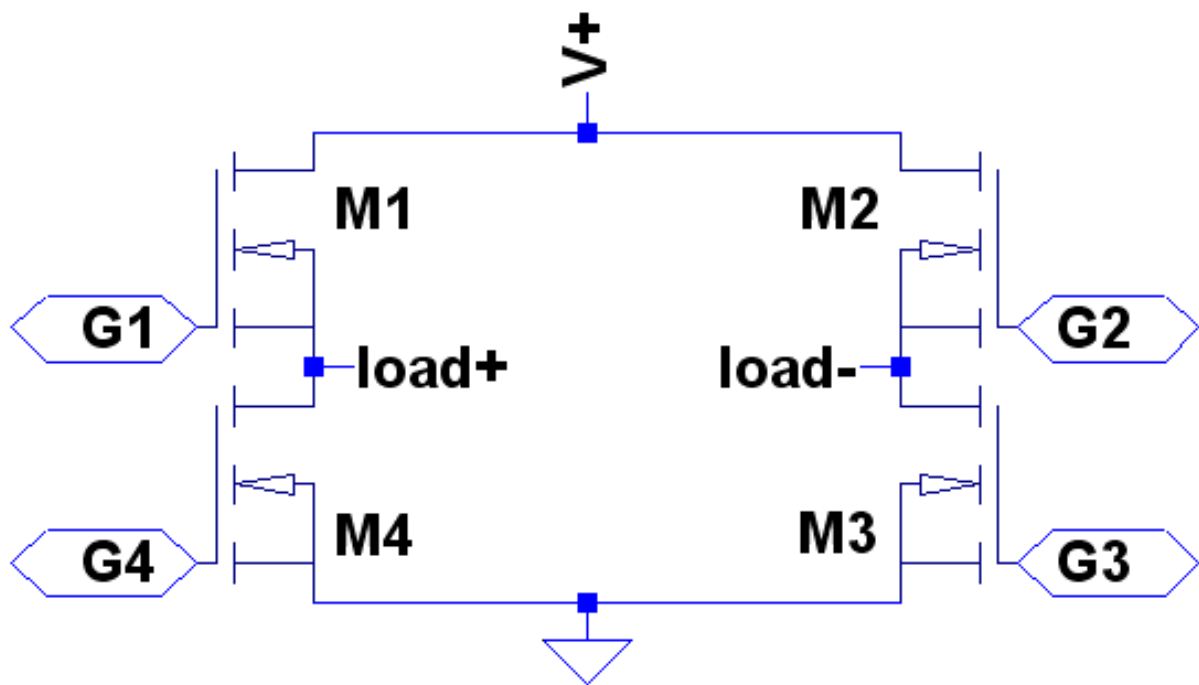


Figure 1: H-Bridge using 4 N-channel mosfets

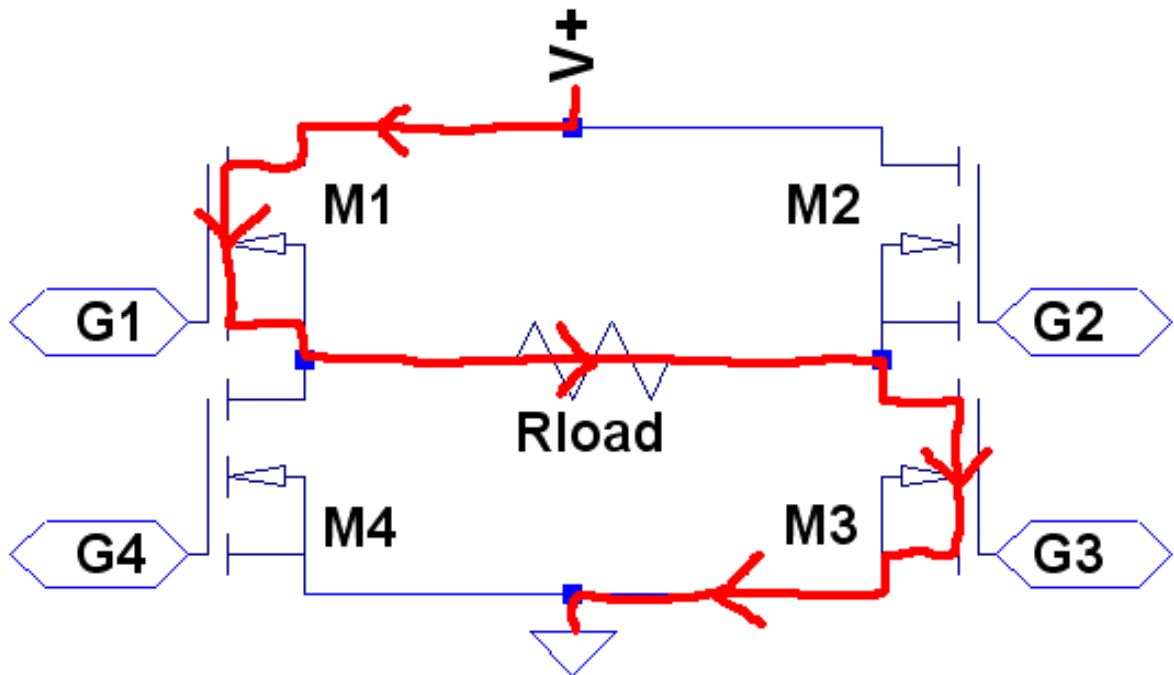


Figure 2: H-Bridge conduction when M1 and M3 are on

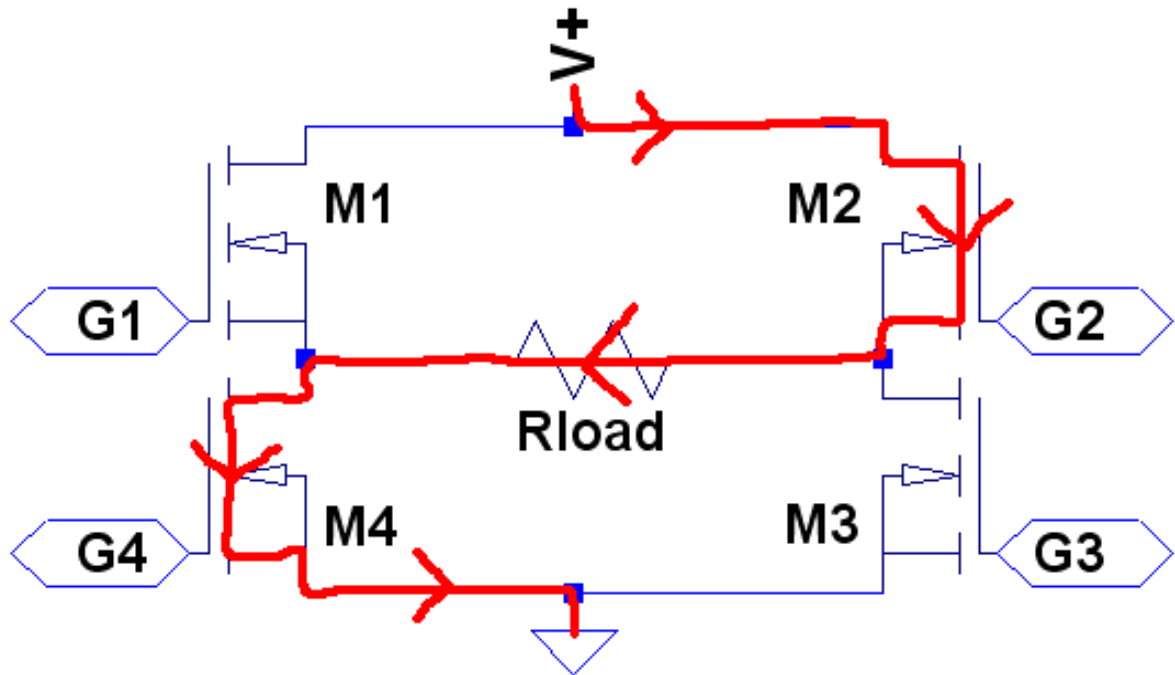


Figure 3: H-Bridge conduction when M2 and M4 are on

PWM generator

A PWM generator consists of a comparator that is fed the input audio signal, and a reference triangle waveform. The output of the comparator will be a PWM signal whose frequency is that of the reference triangle and the duty cycle corresponds to the amplitude of the input audio signal. From a mathematical standpoint this alone is enough to run an H-bridge, but in practice it is nearly impossible. At the transition the top transistor would try to turn off instantly, and the bottom would try to turn on instantly. Since the devices take a certain amount of time to turn off fully, there will be a period of time where both switches will be partially on. The two partially on transistors in series become a low impedance path between voltage rails causing a large spike in current called “shoot through”. A practical solution to this is to add dead time to the switching signals, which will delay the turning on of a device a fixed amount of time, so that the other device is given enough time to fully turn off. This is accomplished by adding a DC offset to the triangle reference waveform of the comparator. One comparator uses a signal that is shifted up, the other uses a signal that is shifted down, and the resulting signals will not be on at the same time[7].

A PWM example is shown in Figure 4 below where a 40kHz 5Vpp sinusoidal waveform is modulated by a 400kHz 5Vpp triangle wave. Whenever the reference triangle waveform is larger than the sinusoid the output waveform, shown in red, is set to 5V. Whenever the reference triangle is lower than the sinusoid the output is low. The FFT of the PWM output is shown in Figure 5. The first peak occurs at 40kHz, and the next largest peak occurs at 400kHz indicating the frequency content of the output is composed of the reference frequency and the sinusoidal frequency. In the figure there are additional spikes around the switching frequency due to dead time in the output waveform. The dead time prevents cross conduction in the outputs but will introduce switching noise above and below the frequency of switching.

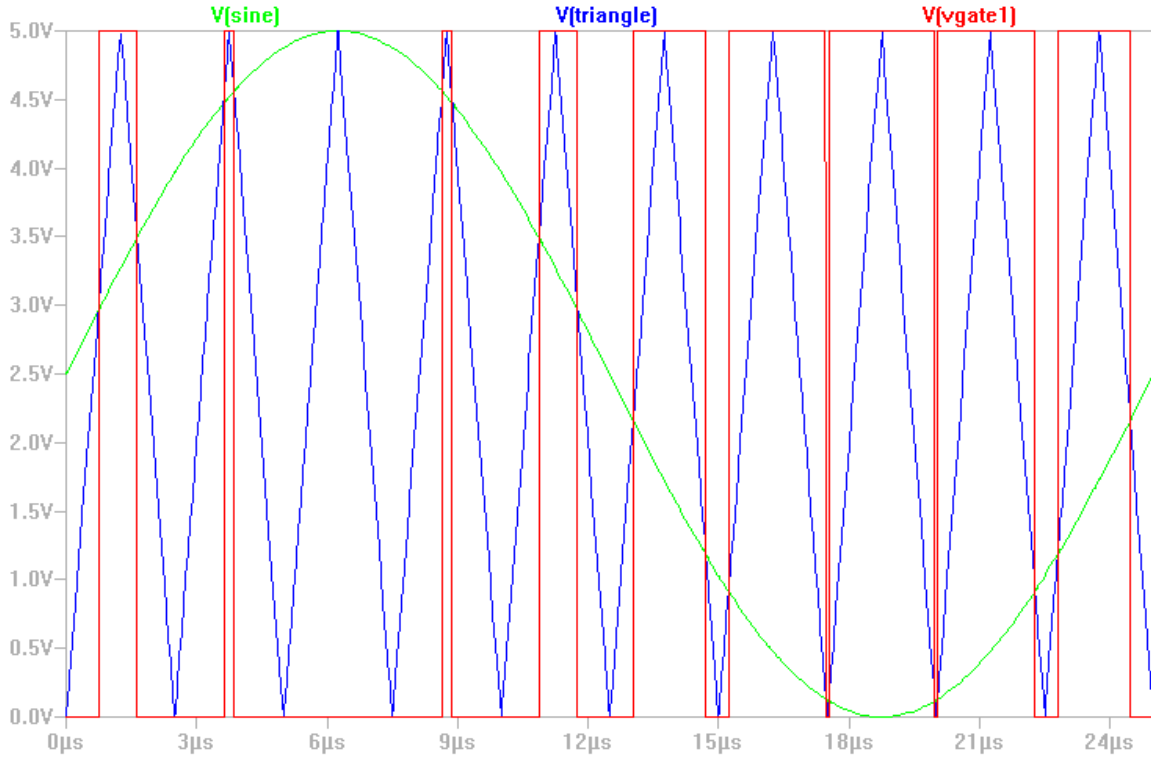


Figure 4: PWM example using triangle wave to modulate a sine. Output is red trace.

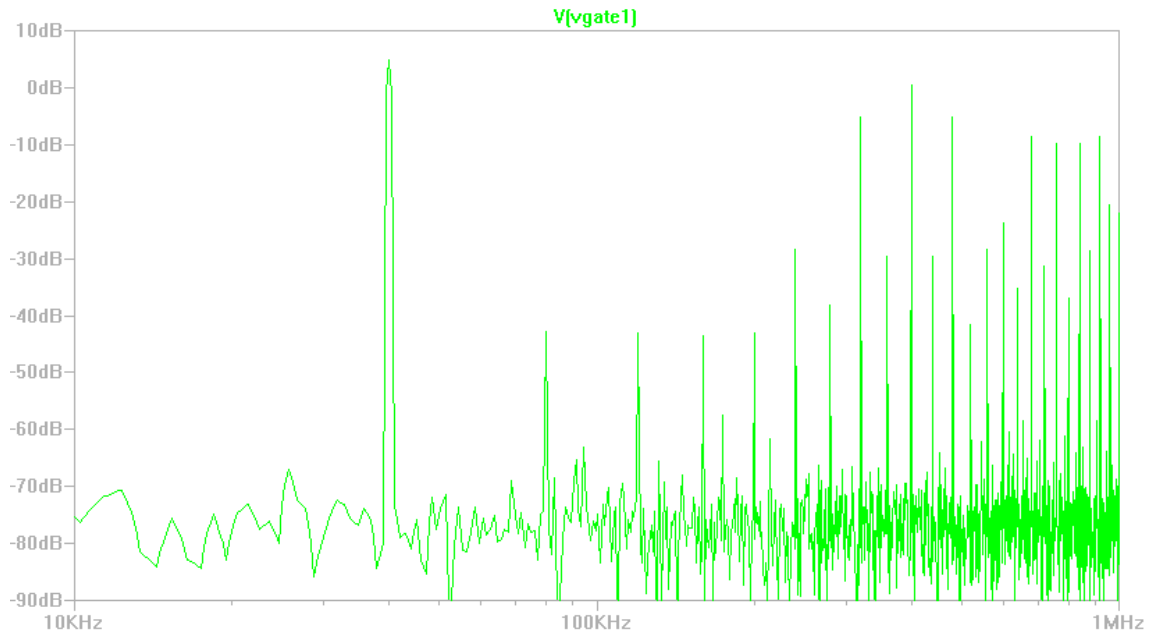


Figure 5: FFT of PWM output

Gate Driver

At high frequencies MOSFETs cannot be driven by high impedance sources so gate drivers are used instead. They are able to switch the transistors on and off at high frequency and perform other functions such as shoot through protection and dead time insertion[8]. One issue is a N-channel MOSFET's mode of operation is governed by its gate to source voltage, which is straightforward for the MOSFET that is connected to ground. The top MOSFET's

source isn't connected to ground so managing its gate to source voltage is difficult but the gate driver takes care of that. For example, if a MOSFET has a gate charge (Q_g) of 10nC and needs to be switched on in 10nS the average current required during the switching period is:

$$\begin{aligned}I_{ave} &= C/S \\I_{ave} &= 10\text{nC}/10\text{nS} \\I_{ave} &= 1\text{A}\end{aligned}$$

Without circuit specifically designed to give this large current in a short period of time the MOSFET can take a large period of time to turn on and off causing huge switching losses.

IRS2092

This chip incorporates a PWM generator, gate driver, and several other features. It is designed specifically for class D audio applications and incorporates many of the necessary components into a single package. It contains a half bridge driver, which can be configured to operate as a full bridge driver by adding a second IRS2092. It can handle up to 200Vdc between the two voltage rails which gives a large safety factor. For the first half of the project the IRS2092 was used, but the TPA3125 replaced it[6].

TPA3125

This chip is a class D amplifier in a 20 pin DIP package. It operates off of a single power rail which allows for a simple power supply. The chip contains two amplifier channels with each amplifier taking a differential signal input. Each amplifier channel outputs on a built in half-bridge so only an external output filter is needed to complete the amplifier. These can be used in an H-bridge configuration by providing the inputs with two equal but opposite signals and attaching the load across the two outputs.

Rotary Encoder

A rotary encoder comes in several different designs but the main features are the ability to turn it an unlimited amount of times. The encoder used in this project outputs using quadrature format which allows the micro-controller to track the movement of the encoder. Quadrature format is measured using two wires and watching the rising edges as shown in Figure 6. The voltage on both channels are saved, and then measured again later. If the knob turned one direction, the output will change one way, but if the knob was turned the other direction the output will change the other way. By sampling often enough and keeping track of the previous states, the motion of the knob can be determined. One drawback is that the actual position of the knob cannot be measured.

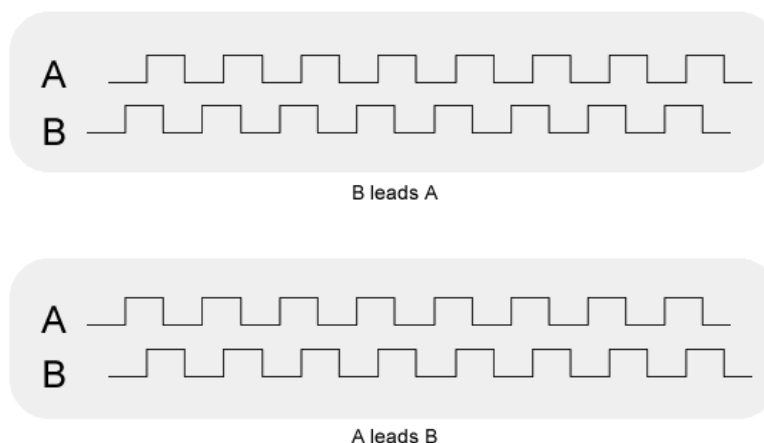


Figure 6: Output waveform for a quadrature rotary encoder

LTC3803

This integrated circuit is specifically designed to control flyback converters. The package information and pin functionality is shown in Figure 7. The main features are an error amplifier with built in reference, gate driver, and current sensor. The error amplifier is used to measure the output voltage and adjust operation to bring it closer to the desired output voltage. The inverting input is attached to pin 3 and the output is connected to pin 1. Pin 6 is the gate driver which can source and sink a significant amount of current allowing the MOSFET to be turned on or off quickly. The current sensor is connected to pin 4 and measures the voltage across a low value resistor and if the voltage is large enough the MOSFET is turned off which limits the maximum current through the MOSFET[9].

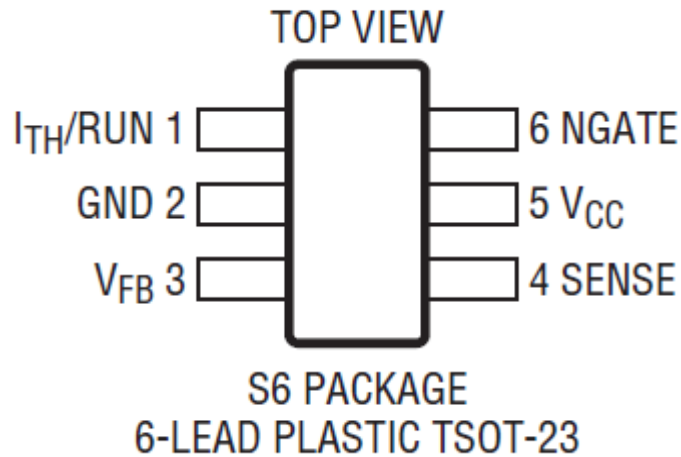


Figure 7: LTC3803 pin functions

Design

The design process began in the Fall of 2011 in EE460 where we developed our projects. Once I decided to build a high efficiency audio amplifier the next step was to decide what was specifically involved and come up with requirements and specifications. The original requirements and specifications are shown in Table 1 below. The first specification is the main feature of this project that makes it different to many commercially available amplifiers. The remaining specifications are all to make sure that it will perform functionally the same as any commercial equivalent. This is important because people will usually not opt to get a more efficient model unless it can perform equal or better at the same or less cost.

The system was then modeled in block diagram form. The level zero block diagram is shown in Table 2, 3, and Figure 8 below. The inputs and outputs are all that the user would be able to interact with. They consist of the audio input and output, power input, and the various user controls.

The project is then broken up in a level one block diagram shown in Table 4, 5, 6, and Figure 9 below. The level zero block diagram has been broken up to reveal the basic subsystems and how they are connected. The subsystems are:

- Power supply – The circuitry required to convert the incoming power as needed to the other subsystems.
- Audio amplifier – The portion which accepts an audio input and outputs an amplified version.
- Logic – The circuitry that controls the operation of the amplifier.
- Display – Allows the user to see how the amplifier is operating.

High Efficiency Audio Amplifier	
Grant Moore EE 460-03	EE 463/464 Dale Dolan 1. I agree to supervise this senior project. _____ 2. The specifications are [1]-[2]: <input type="checkbox"/> Abstract—Describes what project should do, not how. <input type="checkbox"/> Bounded—Identify project boundaries, scope, and context <input type="checkbox"/> Complete—Include all the requirements identified by the customer, as well as those needed to define the project. <input type="checkbox"/> Unambiguous—Concisely state one clear meaning. <input type="checkbox"/> Verifiable—A test can prove if system meets specification. <input type="checkbox"/> Traceable—Each engineering specification serves at least one marketing requirement.
ADVISORS: Please initial above, if you agree to supervise this senior project. Also, please check applicable boxes above. Comment below, if requirements or specifications require revision.	

Marketing Requirements	Engineering Specifications	Justification
1	1. The overall efficiency of the system will be greater than 70% when supplying more than 5 watts to each channel.	Output stages can be up to 95% efficient, and power supplies can be around 80% efficient. 70% efficiency should be easily obtainable.
2	2. System diagnostics will be available to the user displaying the following information: Power usage, temperature, time, and errors.	User will be able to monitor the amplifier performance and easily read error messages. Time will be included for convenience.
5	3. The following controls are available to the user: Power switch, mute, volume, and input selection.	These are basic functionality that are standard on most amplifiers sold today. The minimalist design will make it easy to use.
234	4. Deliver at least 15 watts per channel to speakers ranging in nominal impedance from 4 to 8ohms.	15 watts is adequate for most music listening, and almost all speakers are between 4 and 8 ohms so the amp is compatible with almost any existing setup.
3	5. Total Harmonic Distortion (THD) below 15W will be less than .1% at any frequency between 20-20kHz	This is achievable as most amplifiers are much less than .1% THD until they approach their power limits.
1245	6. Overall weight less than 10 pounds	This is a reasonable weight limit, being lighter than most amplifiers with similar power, allowing it to be easily carried.
1245	7. Overall size less than 12" x 12" x 4" (l, w, h)	The amplifier should be smaller than most amplifiers rated for equal power, which makes these dimensions reasonable.
Marketing Requirements <ol style="list-style-type: none"> High Efficiency Integrates well with any existing system Sounds great Powerful enough to use with large setups, yet small enough to be portable. Easy to use 		

Table 1: Requirements and specifications for this project

Level 0 Block Diagram

Inputs –

Power	This connection gives the amplifier power it needs to amplify the signal, power any logic etc.
Audio Signal Input	The audio signal to be amplified.
Volume	The volume control that the user uses to raise or lower the output volume of the amplifier.
Power Switch	The power switch is what the user turns the amplifier on or off with.
Mute	The mute button toggles the output volume between zero and the volume selected by the user.

Table 2: List of inputs of the high efficiency audio amplifier

Outputs –

Audio outputs	The amplified versions of the audio inputs that are used to power speakers.
System information	Information about the amplifier such as temperature, output power, errors etc.

Table 3: List of outputs of the high efficiency audio amplifier

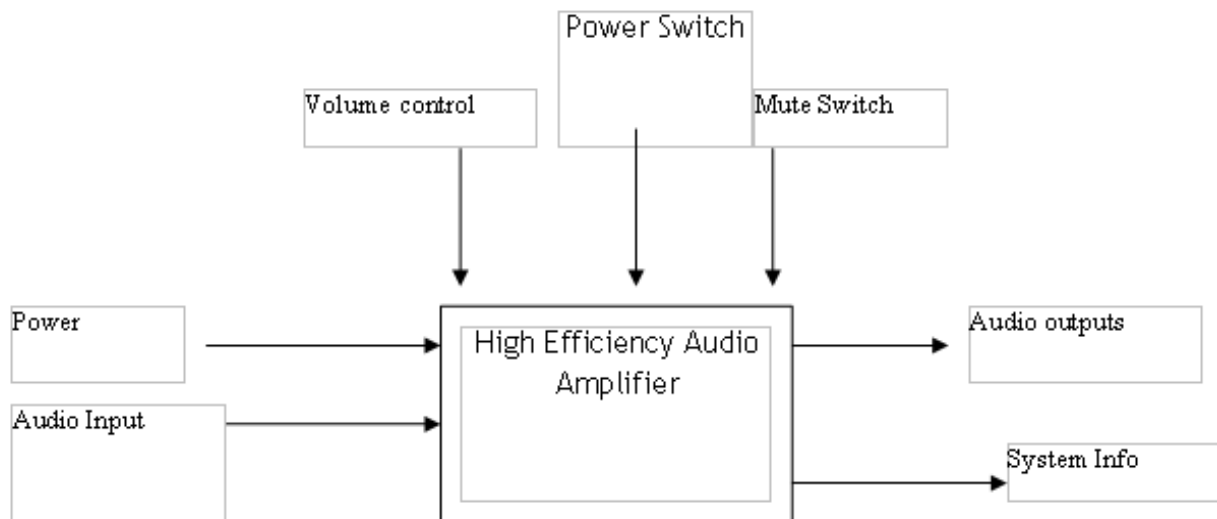


Figure 8: Level 0 block diagram of the high efficiency audio amplifier

Level 1 Block Diagram

Inputs

Power	This connection gives the amplifier power it needs to amplify the signal, power any logic, etc.
Audio In	The audio signal to be amplified.
Volume	The volume control for the user to raise or lower the output volume of the amplifier with.
Power Switch	The power switch is what the user turns the amplifier on or off with.
Mute	The mute button toggles the output volume between zero and the volume selected by the user.

Table 4: List of Level 1 inputs of the high efficiency audio amplifier

In/Outs

Logic Power	Power supplied by the power supply to the logic to operate correctly
Amplifier Power	Power supplied by the power supply to the amplifier
Display Power	Power supplied by the power supply to the display
Information	Data sent to the display by the logic which is to be outputted to the user.

Table 5: List of Level 1 inputs/outputs of the high efficiency audio amplifier

Outputs

Audio outputs	The amplified versions of the audio inputs that are used to power speakers.
Info Out	Information about the amplifier such as temperature, output power, errors etc.

Table 6: List of Level 1 outputs of the high efficiency audio amplifier

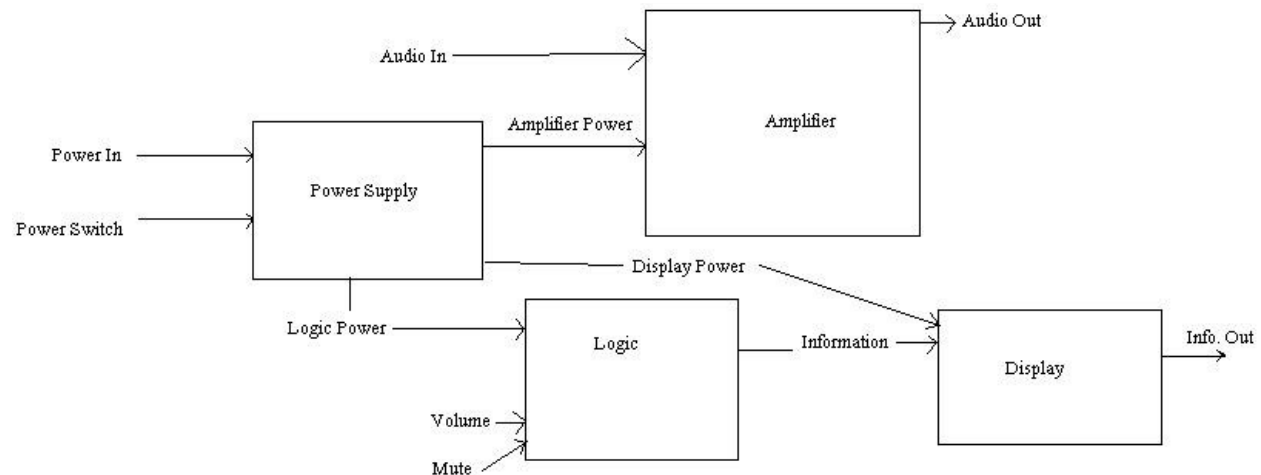


Figure 9: Level 1 block diagram for the high efficiency audio amplifier

Power Supply Design

Choosing Power Supply Parameters

There are several design considerations when choosing a power supply because some power supplies may serve very well in some applications, but perform poorly in others. Therefore it is important to optimize the power supply to suit the project[10].

The first step in choosing a power supply is to figure out the requirements, and for a good audio power supply it must be:

- Isolated – This means there is a transformer between the wall, and the rest of the circuit. This serves two functions. First it adds a level of safety in the event that the power supply is shorted. The transformer will saturate and limit the current draw before it gets dangerous. Without the transformer the power supply could turn into an arc welder until the circuit breaker is tripped. Second, the transformer serves to allow the output to be stepped up/down relative to the input. This allows the user to optimize the operation so that the converter doesn't have to use extreme duty cycles.
- DC output with very low ripple – By nature an H-bridge will have a line regulation of 100%, meaning that the output voltage will change directly with a changing input voltage. The voltage ripple will need to be kept below a certain threshold so that it won't affect the output and contribute to THD. The amplifier does utilize a negative feedback loop, but the disturbances from the power supply may be too much for the controller to respond. Therefore the output voltage ripple should be kept to a minimum.
- Handle large transients – Audio signals can range in amplitude from 0V all the way to clipping, and most will spend significant amounts of time at different amplitudes. It is expected to see current requirements change suddenly from 0A to full power in very short periods of time and often. The power supply will therefore need to operate correctly over a wide range of loads, and be able to respond quickly to changing loads.

Choosing DC supply voltage

The key considerations when choosing the output voltage are:

- Output power requirement – The maximum power that can be delivered to identical loads will be increased when using large voltage rails. The output voltage must be chosen so that the power requirements are met, and then headroom should also be included. Assuming lossless transistors the voltage required to deliver 15W to an 8Ω load is:

$$\begin{aligned}15W &= V_{rms}^2 / 8\Omega \\ V_{rms}^2 &= 120V^2 \\ V_{rms} &= \sqrt{120V} = 10.95V \\ V_{peak} &= \sqrt{2} 10.95V = 15.49V\end{aligned}$$

Since a full bridge topology is used the peak voltage will be applied in both polarities across the load allowing a greater peak to peak voltage than the DC rail. Since the output transistors are not lossless there needs to be additional headroom. According to the datasheet the $R_{ds(on)}$ of the output transistors is typically .21Ω. At 15W output the peak current will be:

$$\begin{aligned}15W &= I_{rms}^2 8\Omega \\ I_{rms}^2 &= 1.875A^2 = 1.369A \\ I_{peak} &= \sqrt{2} 1.369A = 1.936A\end{aligned}$$

The minimum DC rail voltage is revised using losses in the mosfets:

$$V_{rail} = 15.49V + 2V_{fet}$$

$$V_{fet} = I_{peak} * R_{ds(on)} = .407V$$

$$V_{rail} = 16.3V$$

- Efficiency – the efficiency is directly related to the ratio of output power to maximum power. As the amplifier operates closer and closer to its maximum output power, the efficiency will increase. The biggest difference in efficiency between two voltage rails occurs at very low power levels. At higher levels all will approach their asymptotes which are very close to each other. As is in Figure 10 below from the range of 0W to 2W output power, the efficiency difference will be most notable. For audio applications most audio will remain below half maximum power for the majority of time. Because of this it is important to get maximum efficiency at low power levels[11].
- Convenience, and practicality – the output voltage should be relatively easy to obtain, special or boutique parts shouldn't be needed. Common voltages such as 12, 24, and 36V should be used rather than 21V or other uncommon voltages. In terms of practicality, 300Vdc might be common in some applications with many parts readily available, but it isn't well suited for use in an audio amplifier. If the output is chosen so that system components are able to be powered from it, the overall design will be simplified by eliminating extra power supplies.

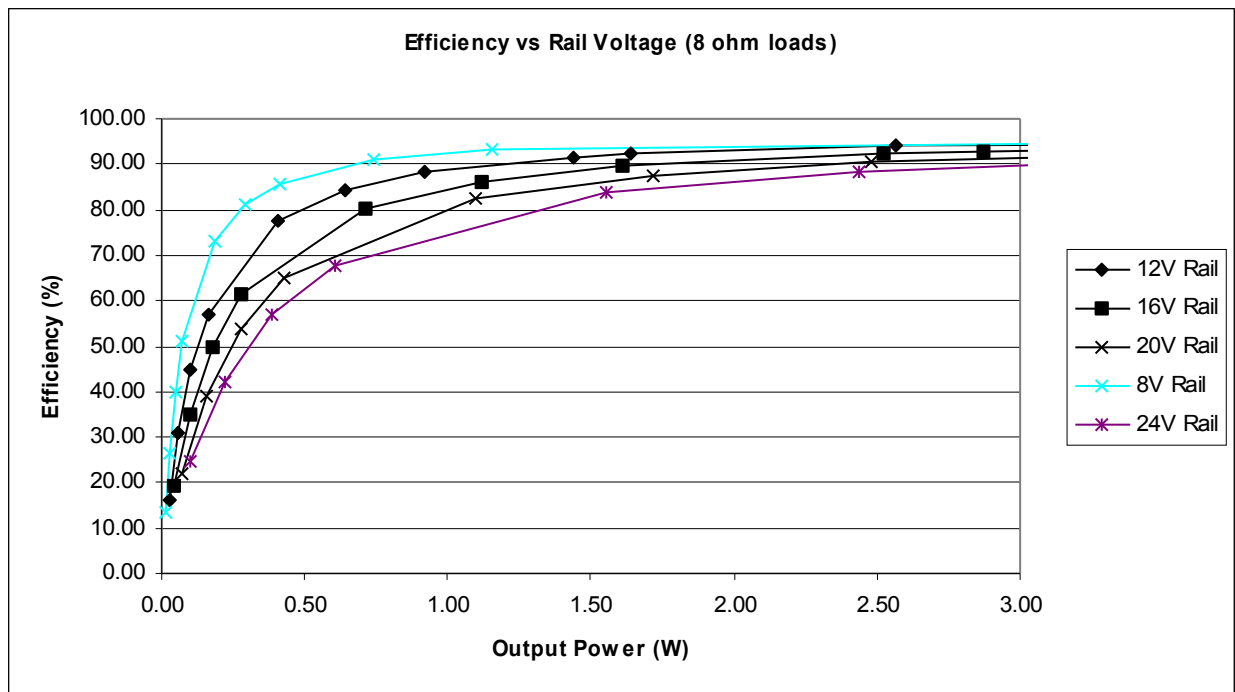


Figure 10: Efficiency of amplifier for different rail voltages

Choosing Power Supply Topologies

The efficiency requirement limits the options to switch mode power supplies, and the isolation requirement limits the flyback and forward dc-dc converters. The flyback is the preferred choice because a forward converter requires a minimum load or else the output voltage will continually increase. This can be tolerable in applications where a fixed load is being driven but not for an audio amplifier. An audio amplifier acts as a variable load and operates most of the time as a low load. Using a forward converter with a very light load will result in a very inefficient system. Therefore a flyback converter was chosen. A flyback converter also has the advantage of needing less parts, resulting in a simpler circuit.

Flyback Converter Design

The LTC3803 PWM controller was chosen because it is a very simple chip and is designed for controlling flyback converters. The converter was designed using LTSpice, starting with the example circuit for the LTC3803. Since

the incoming voltage will be rectified 120Vac, the input voltage to the circuit was set to 170Vdc. The most critical component to the design is the transformer, so possible transformers were researched so that simulation results would be meaningful. To choose a transformer, the output current was known to be 4A continuous at maximum output. This corresponds to an input current of 1.333A average or 2.5A peak since almost all the available transformers had a turns ratio of 3:1. The transformer was chosen so that it would not saturate based on the current requirements. The other criteria were that it needed to handle 170Vdc and was designed to operate around 200kHz. The chosen transformer was a Wurth Once the transformer was chosen, all its specs were incorporated into the LTSpice project so that simulations would be very accurate.

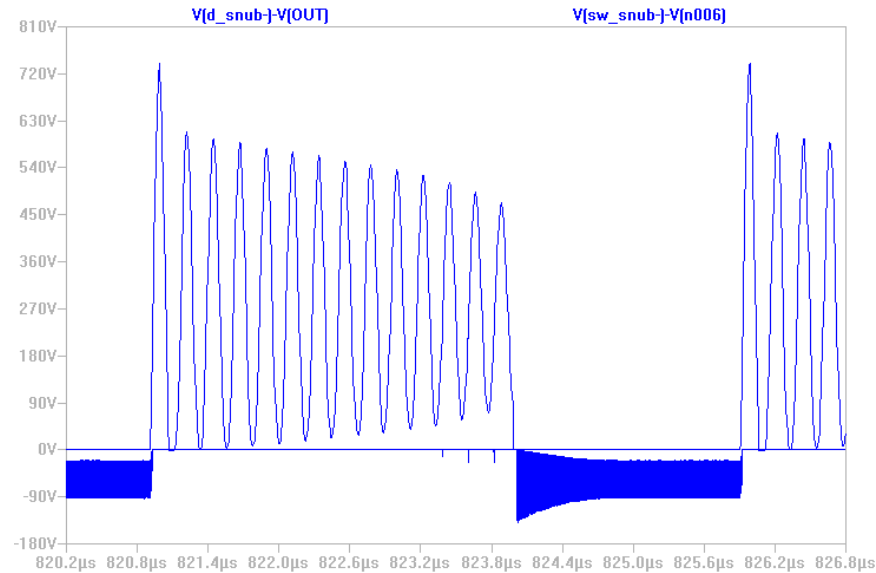


Figure 11: Voltage ringing at across MOSFET (top trace) and across diode (bottom trace) at full load

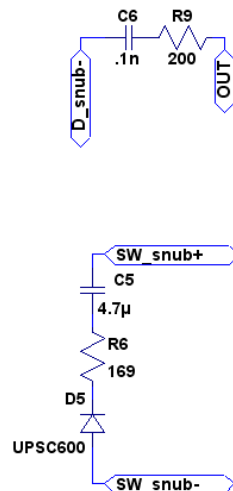


Figure 12: Snubber circuits added across MOSFET and diode to prevent ringing

The first problem was that when the leakage flux was entered, this caused severe voltage and current ringing across the switch and diode which would simply destroy them if the circuit was built as is [12],[13]. Flyback ringing is a fairly common problem and there are several ways to address them, the most common ways are to use an RCD

snubber across the primary side. When the switch is on the diode is reverse biased, but as soon as the switch turns off the diode becomes forward biased by the flyback voltage. This voltage spike charges up the capacitor which in effect absorbs the transient voltage spikes. The ringing of the converter is shown in Figure 11 without any snubber circuit.

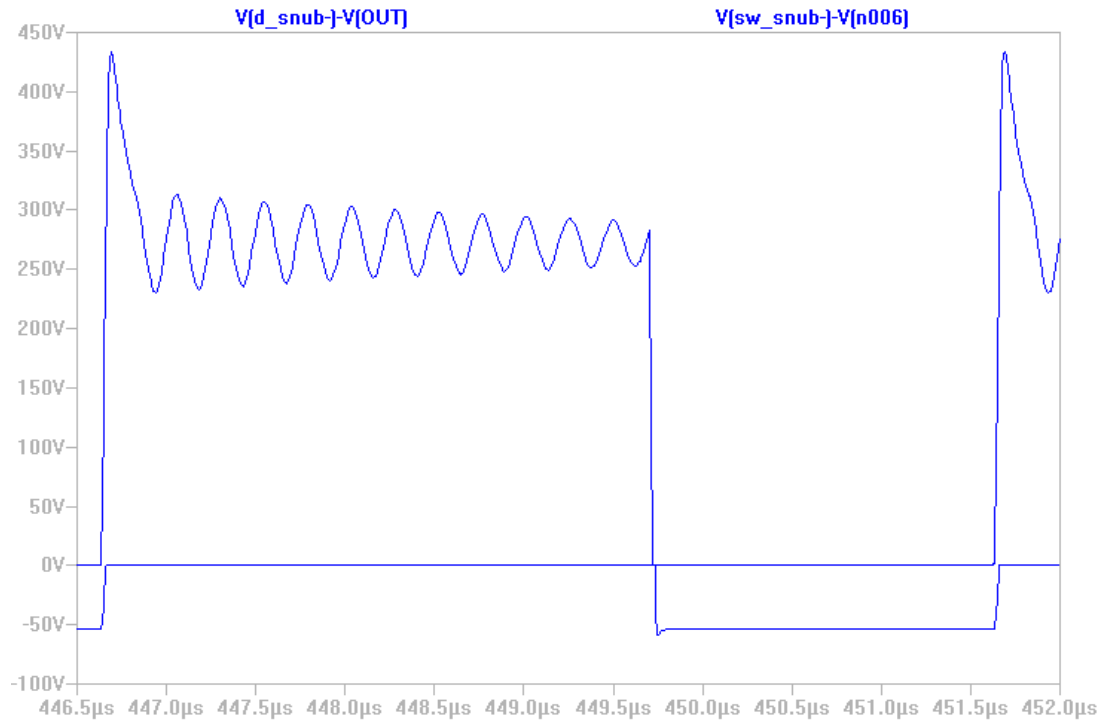


Figure 13: Voltage ringing with snubbers across MOSFET (top trace) and across diode (bottom trace) at full load

The MOSFET snubber circuit was made by inserting a resistor, capacitor and diode in series in parallel with the MOSFET. When the MOSFET turns off and a large voltage is reflected on its positive the snubber diode becomes forward biased and the capacitor is charged up limiting the transient voltage spike across the MOSFET. The results of using the RCD snubber shown in Figure 12 improves the voltage ringing across the switch and diode shown in Figure 13. This has made a significant improvement in the ringing. The voltage peak only goes up to 430V and the oscillation isn't as severe. The energy in the leakage inductance has been successfully dissipated which improved the ringing in all areas of the converter. The diode snubber operates in the same manner, but a series diode isn't needed since reverse conduction isn't an issue.

The resulting circuit is shown in Figure 14 and 15. Figure 14 shows the bridge rectifier and filter which converts the incoming 120Vac into DC. Figure 14 also contains the controller which is hooked up to the rest of the circuit using ports. Figure 15 contains the main portion of the converter. The leftmost pieces are the primary side of the transformer and the MOSFET switch. Attached to the secondary side of the transformer is the feedback resistor network, the blocking diode, and the output filter. The output filter consists of several individual capacitors to both increase the effective capacitance and lower the ESR since a single capacitor that could operate the same would cost much more than the group. The pieces off to the sides in Figure 15 are the snubber circuits which are used to limit any transient voltages that would otherwise hurt sensitive portions of the circuit[14],[15].

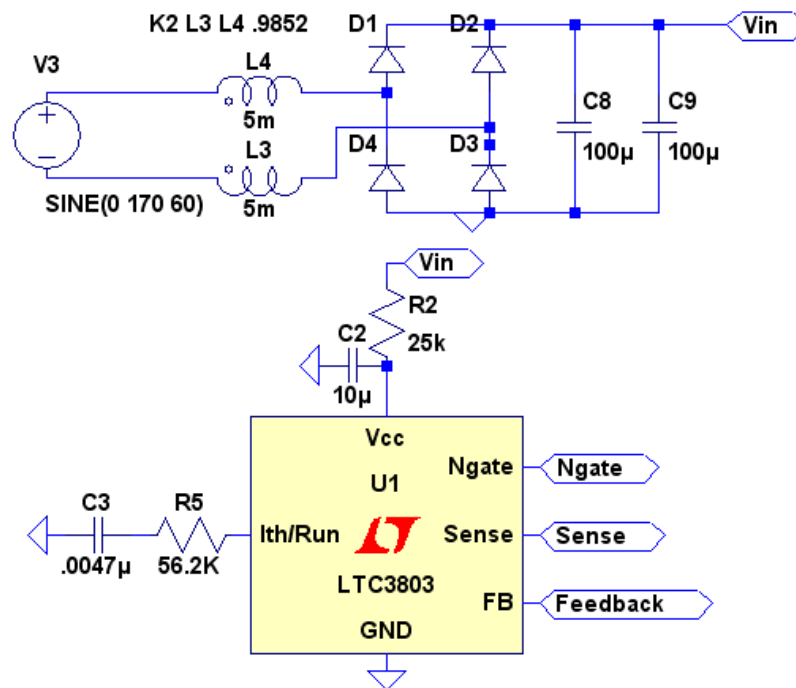


Figure 14: Controller and AC rectifier portion of flyback converters

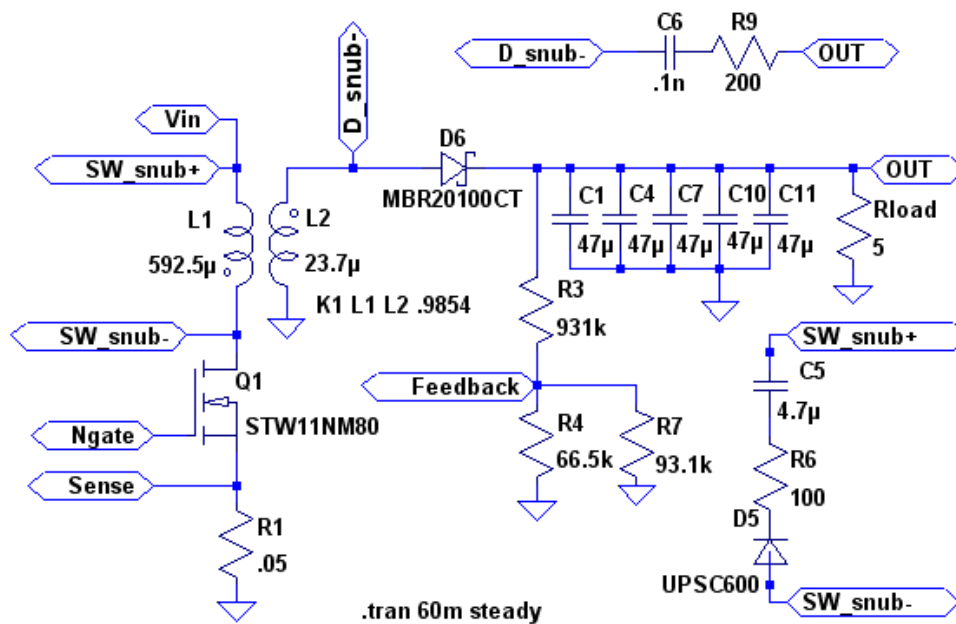


Figure 15: Snubbers and Main portion of flyback converter

Power Supply Board Design

The PCB was designed in PCB Eagle and the resulting top and bottom layers are shown in Figure 16 and 17. The board was then etched by printing the designs out with a laser printer, ironing then onto a double sided copper clad board, then putting the boards in a muriatic, hydrogen peroxide solution. The resulting board is shown in Figure 18 and 19. The components were then soldered onto the board and is shown in Figure 20.

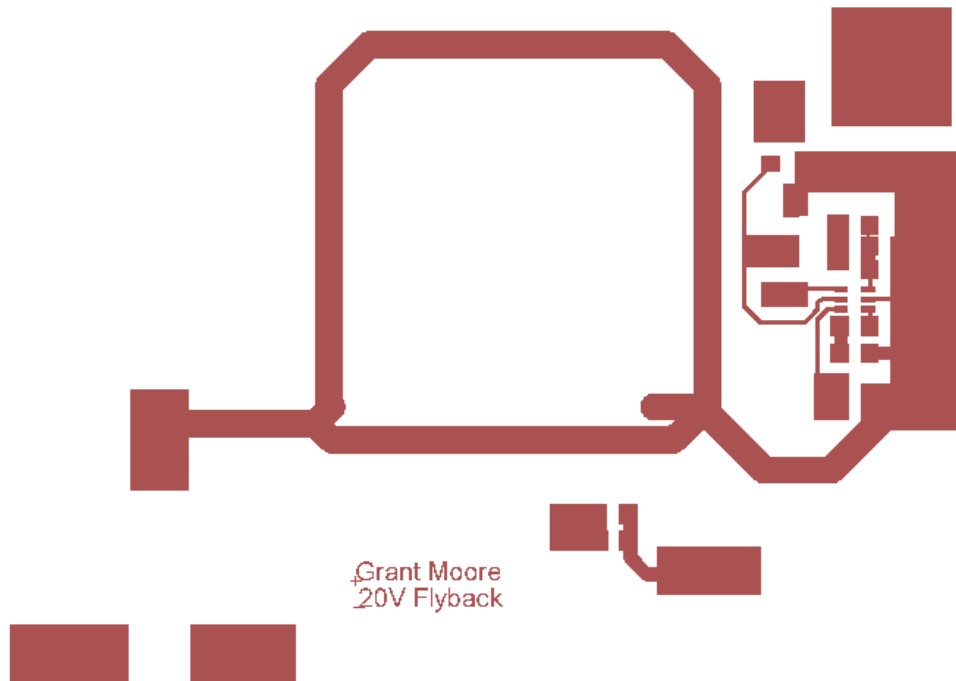


Figure 16: Top Layer of PCB

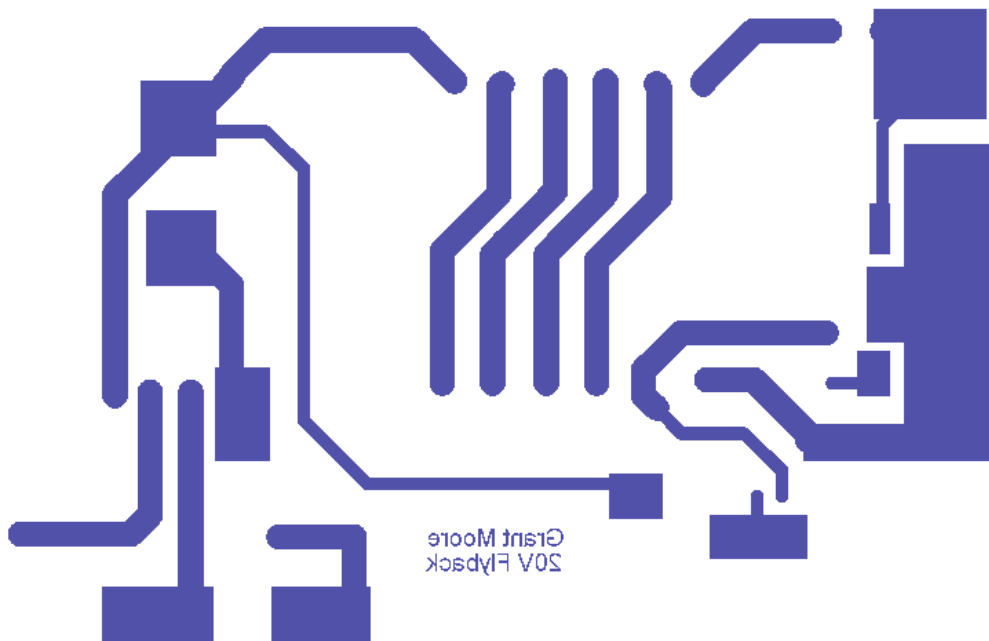


Figure 17: Bottom Layer of PCB (Mirrored)

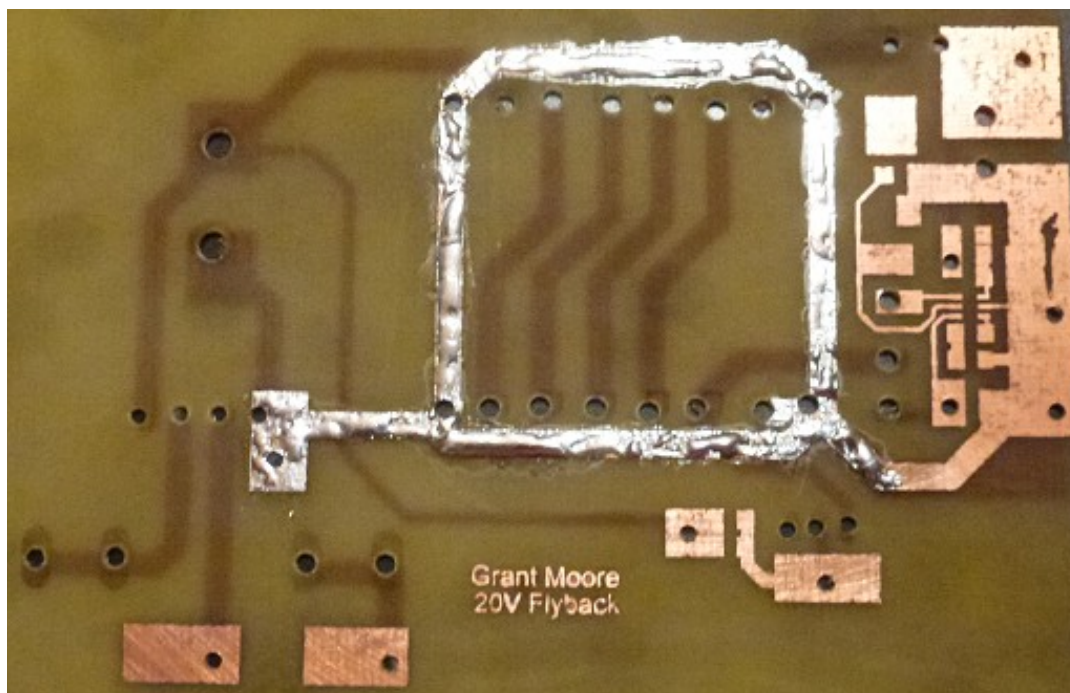


Figure 18: Top Layer of etched PCB with solder added

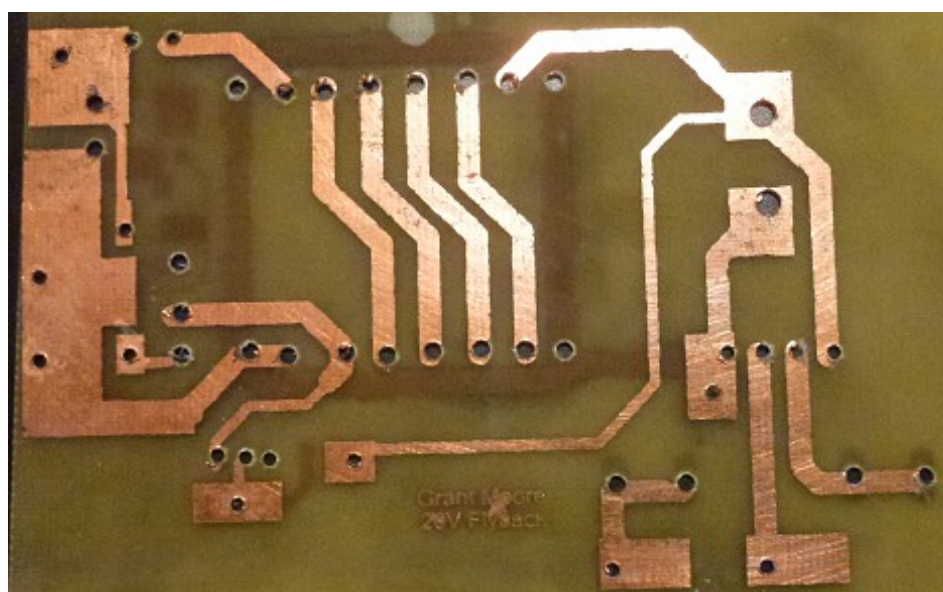


Figure 19: Bottom Layer of Etched PCB

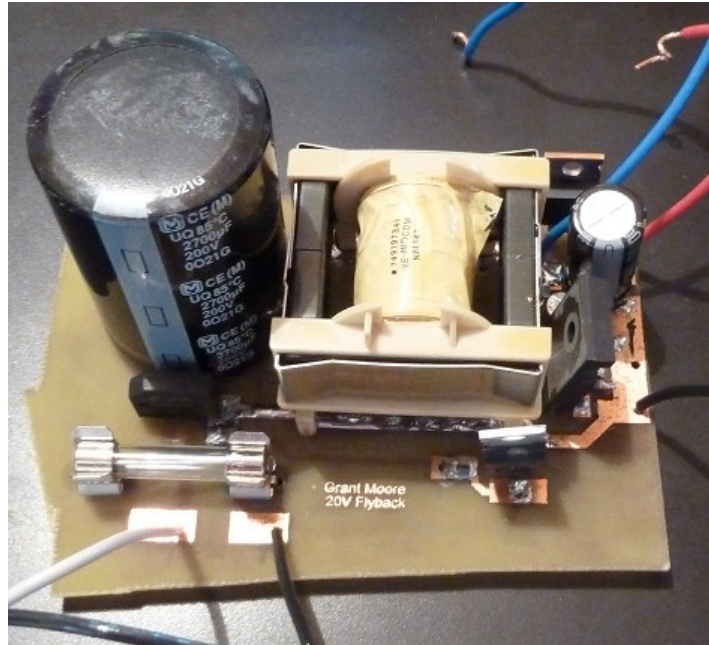


Figure 20: Fully Assembled board

Testing

The converter was connected to 120Vac with the hot connected through the fuse on the board. The output was connected to a multimeter which was set to measure DC voltage. When power was applied the fuse would instantly fail indicating that substantial current was being pulled.

Shortcomings of this design

- The inrush current of the filter capacitor(2700uF) is very large(About 70A during first half cycle according to simulation) which causes the fuse to blow instantly even though it is a slow blow. A soft start circuit would help limit the inrush current.
- There were errors in the schematic layout because I mixed up the pins on the LTC3803, and reversed the pinout of the schottky diodes. Luckily I was able to bend the legs of the diodes to get them to fit, and the reversed LTC3803 pins only needed the MOSFET reversed and the sense resistor moved.
- Incorporating terminal blocks would increase board aesthetics and make the converter much easier to connect up.
- Some devices are much larger than necessary and switching them with more appropriately sized devices would reduce board real estate and component cost. These include the diodes, the MOSFET, and the input and output capacitors.
- LTC3803 must be powered from an external supply, which is much less practical than having it self power from the line voltage.
- Snubbers were unable to suppress voltage ringing effectively.

Version 2

The main shortcoming of the first design was that the input voltage was assumed to be within the range of 153Vdc to 187Vdc which corresponds to a rectified 120Vac input. In a linear regulated power supply, the incoming voltage is simply passed through a bridge rectifier and the passed through a large filter capacitor which removes enough of the ripple so that the voltage regulator can work properly. In version one I simply put a bridge rectifier and a large filter capacitor to accomplish the same task but this created a big problem. When the circuit is first energized the capacitor is charged to 0Vdc and acts like a short circuit. This causes a large inrush of current that is usually tolerable in linear power supplies because they will use a transformer in front of the bridge rectifier so the initial voltage across the capacitor is usually less than 48Vdc. But in this switching power supply there isn't a transformer

before the bridge rectifier and the capacitor will receive the entire 153Vdc to 187Vdc. The resulting inrush can be upwards of 80A during the first half cycle which will destroy any low amperage fuse regardless if it is a slow blow.

To alleviate this problem two main changes were made to the rectifier circuitry in the flyback converter. First the filter capacitor was sized down to 200uF. This will decrease the charging current spike because the capacitance corresponds to how much charge it takes to raise the voltage. Since the capacitance has been lowered significantly, less charge is required to raise its voltage up to around 170Vdc, corresponding to less current, which reduces the inrush current. The second change is the addition of a 5mH common mode inductor before the bridge rectifier which will reduce the effect of large current spikes and decrease the inrush current even more. A simulation of the original input stage, the original with a smaller capacitor, and the final input stage are shown in Figure 21 below.

Several other issues were resolved in the second version of the flyback converter. The PWM controller is now powered off of the 170Vdc rail through a 25kohm resistor using the controller's internal shunt zener regulator. The resistor value was chosen empirically by simulating the converter for several different resistor values and choosing the one that used the least power but was still able to operate correctly.

The input and output filter capacitors were changed so that they consisted of several in parallel which lowers the effective ESR of the capacitors. Electrolytic capacitors provide a very cost effective solution for bulk capacitance, but have poor ESR which results in increased voltage ripple. By using several in parallel the individual capacitors can be lower capacitance but still from the same low cost family. The resulting capacitor bank costs less, has a lower ESR, and larger overall capacitance from a capacitor of a low impedance family. The downside to this approach is that more board space is required, but in this application it isn't an issue.

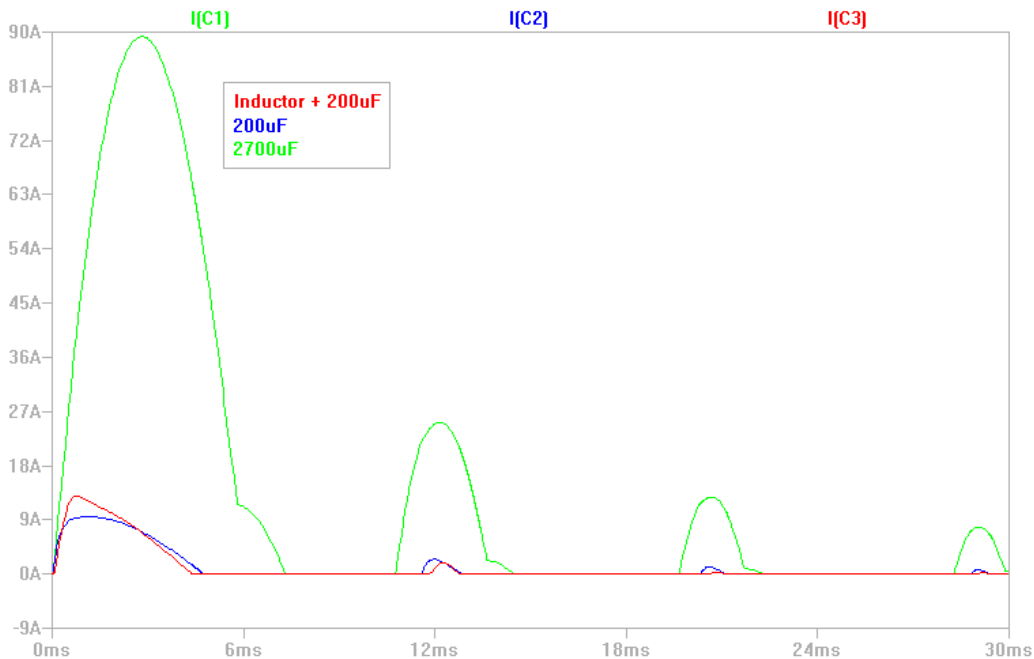


Figure 21: Inrush current for three different input stages.

To improve efficiency the method of powering the IC was changed. The LTC3803 contains an integrated zener regulator so the simplest way to power the chip is to add a resistor in series with the voltage source allowing a wide range of voltage sources. The problem with this is that there will be a large voltage drop across the series resistor which can dissipate a large amount of power. In this application where the incoming voltage is around 170Vdc the power dissipated across the series resistor will generate around 2.5W with the largest recommended resistor value. This power loss is unacceptable for my application and an alternative is needed. Linear Technology recommends a second method for powering the converter using an auxiliary winding of the flyback transformer. The flyback transformer is part of the Coiltronics Versa-Pac transformer series which contains six identical windings to be connected any way the consumer chooses. For the power supply the primary winding consists of four windings connected in series, the secondary winding is just a single winding, and the last winding is used to power the chip.

The converter was simulated from no load to full load in steps of 5% and the results were plotted in Table 7 and Figure 22 below. The simulations are very promising showing efficiencies in the mid 80s and reasonable output voltage ripple.

Testing

The converter was then built and tested at no load in Figure 23 showing proper operation. Interestingly when a small load was applied a puff of smoke came out of the primary snubber network but the converter worked just fine. Upon further investigation the diode had gotten so hot that the solder had melted and capillary action pulled it out of the circuit.

Load (%)	Vout(avg)	Voutpp(%)	Pout	Efficiency (%)
5	20.02	0.58	1.50	53.82
10	20.02	0.80	3.00	71.61
15	20.01	0.99	4.51	76.78
20	20.01	1.15	6.01	78.38
25	20.01	1.26	7.51	81.87
30	20.01	1.37	9.01	84.02
35	20.00	1.49	10.50	83.45
40	20.00	1.59	12.00	83.33
45	20.00	1.69	13.50	84.26
50	20.00	1.78	15.00	85.56
55	20.00	1.87	16.50	85.99
60	20.00	1.95	18.00	85.40
65	20.00	2.04	19.50	84.97
70	20.00	2.11	20.99	85.04
75	19.99	2.19	22.48	85.55
80	19.99	2.26	23.98	86.21
85	19.99	2.33	25.48	86.49
90	19.99	2.40	26.99	86.11
95	19.99	2.47	28.46	85.65
100	19.99	2.54	29.98	85.39

Table 7: Simulated performance of the flyback converter

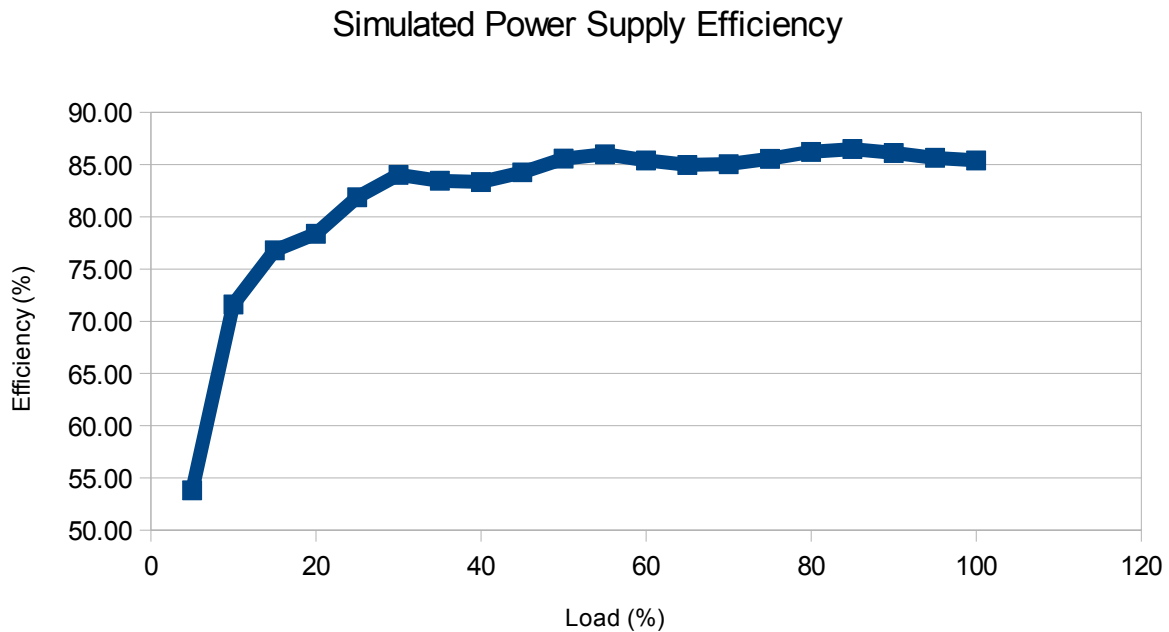


Figure 22: Simulated Power Supply Efficiency



Figure 23: Initial testing showing proper operation of the flyback converter.

The flyback converter needs to be able to deliver 30W at 20Vdc from a supply from a 120Vrms wall socket. The test setup is shown in Figure 24 below. The input current, voltage, and power were all measured with an AC power meter. The output voltage was measured with an Agilent multimeter and a BK Precision electronic load was used to test the performance at various loads. A Scopemeter was used to watch the voltage at the primary side snubber and across the secondary side snubber.

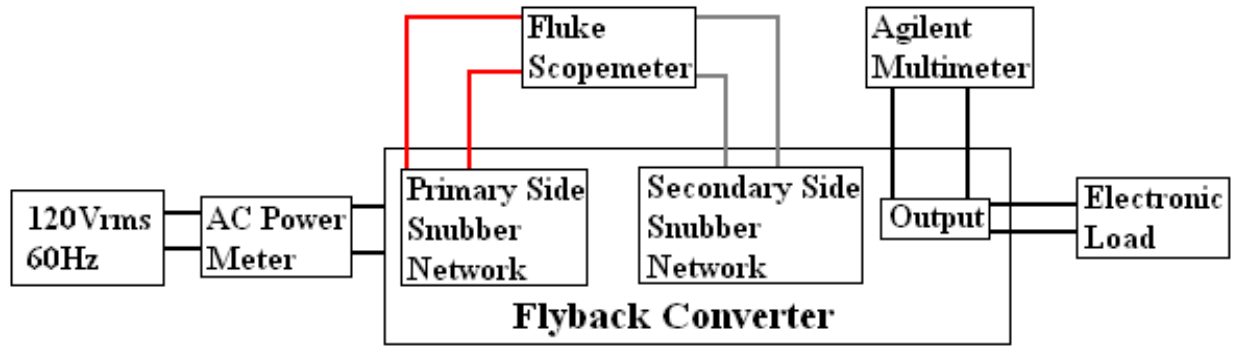


Figure 24: Setup used to test the flyback converter.

During initial testing the primary side snubber resistor would fail and burn up. This was tested by measuring the voltage across the resistor and adjusting the load, and at about 10mA, the resistor would begin to overheat. Since the MOSFET has a breakdown voltage of 650V and the flyback ringing was less than that, the snubber network was removed and all the testing was done without it. The measured data is shown in table 1 below, and the efficiency vs. load is shown in Figure 25 below.

All the data taken below 1A output current was taken normally, but when higher currents were tested the output voltage would fall very slowly, but noticeably. Because of this the load was quickly turned on and measurements taken soon after to allow for steady state, but not enough time for the voltage to fall.

Iout (A _{dc})	Vout (V _{dc})	Pin (W)	Pout (W)	Efficiency (%)
0.024	20.04	0.8	0.48	60.1
0.05	20.06	1.48	1.00	67.8
0.075	20.07	2.11	1.51	71.3
0.1	20.10	2.76	2.01	72.8
0.2	20.09	5.26	4.02	76.4
0.3	20.06	7.74	6.02	77.8
0.4	20.05	9.82	8.02	81.7
0.5	20.03	12.43	10.02	80.6
0.6	20.02	14.74	12.01	81.5
0.7	20.01	16.84	14.01	83.2
0.8	20.03	19.23	16.02	83.3
0.9	19.97	21.6	17.97	83.2
1	19.80	23.8	19.80	83.2
1.1	20.04	26.2	22.04	84.1
1.2	20.09	28.6	24.11	84.3
1.3	20.08	31.2	26.11	83.7
1.4	20.11	34	28.15	82.8
1.5	20.09	36.8	30.13	81.9

Table 8: Measured performance of flyback converter

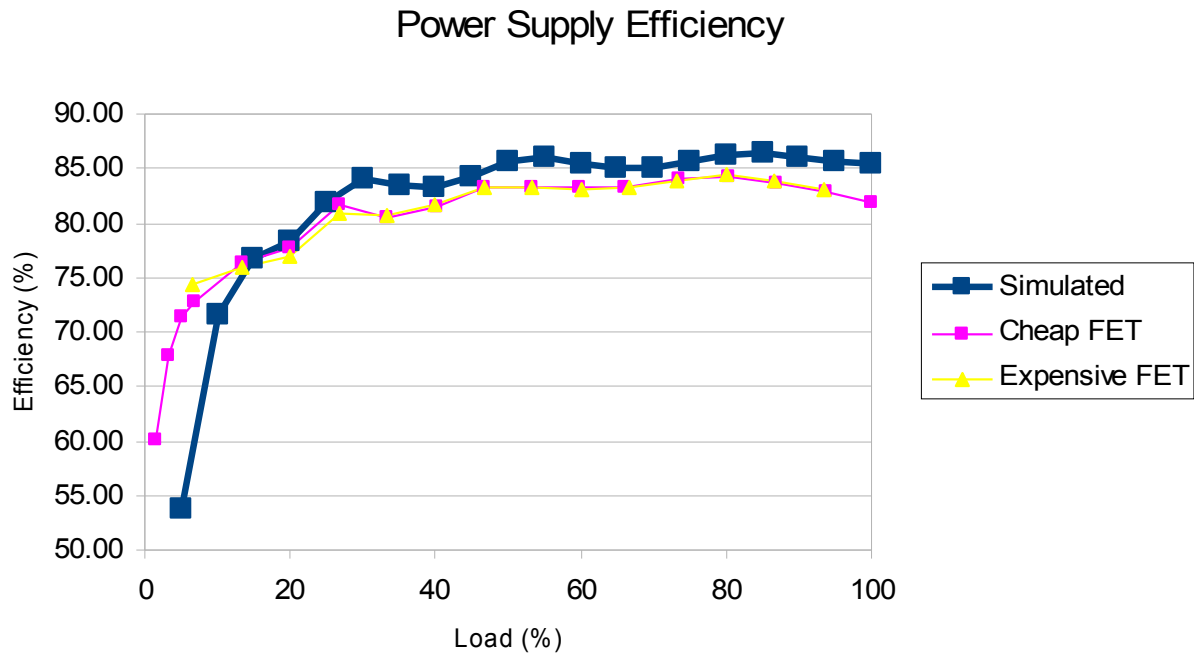


Figure 25: Efficiency vs. Load of the simulated, and measured flyback converter.

Two sets of data were taken, using two different MOSFETs to compare their performance. The first FET had a total gate charge Q_g of 17nC, $R_{ds(on)}$ of .385 ohm and cost \$2.50. The second MOSFET cost only \$.50 and had a much lower Q_g of 6nC at the expense of a 2ohm $R_{ds(on)}$. The two data sets are plotted in Figure 25 above and they performed almost identically showing the extra cost of the expensive MOSFET isn't justified.

The most troubling thing about the performance of the flyback converter was the output ripple. The flyback ringing was not suppressed and would create a 5Vpp ring whenever the MOSFET turned off. This will need to be corrected by using either a second order output filter, or using a diode snubber circuit.

When power was applied to the converter, occasionally it would idle around 2V output and would take a few seconds to turn on fully. This would most likely be caused by the bootstrap winding taking a while to engage. This happened only about twice during the entire testing period so it shouldn't be something to be concerned about.

The efficiency was very good and followed below the simulation curve by about 2%.

Isolating the converter

The conventional method to provide isolation to a switching regulator is to move the error amplifier to the secondary side. The comparator output is then sent to the primary side through an optocoupler which turns the converter on and off. In most designs the error amplifier is implemented using a 431 or similar shunt regulator because it is inexpensive and provides adequate accuracy. The schematic for the isolated feedback loop is shown in Figure 27 and the transfer function shown in Figure 26. The TL431 has a built in 2.5V reference which is compared against a reference pin. If the voltage at the reference pin is greater than 2.5V current will be sunk through the optocoupler. On the primary side the optocoupler transistor saturates and the output voltage will be the saturation voltage of the transistor. When the voltage on the reference pin of the optocoupler is less than 2.5V the optocoupler will be off and the output voltage of the secondary side will pull up to 8V. The output voltage of the power supply will be connected to the feedback network, and the output voltage will be connected to the compensation pin of the LTC3803. The result will be a converter that operates at full power when the output voltage is less than 20V, and turns off when the output is over 20V.

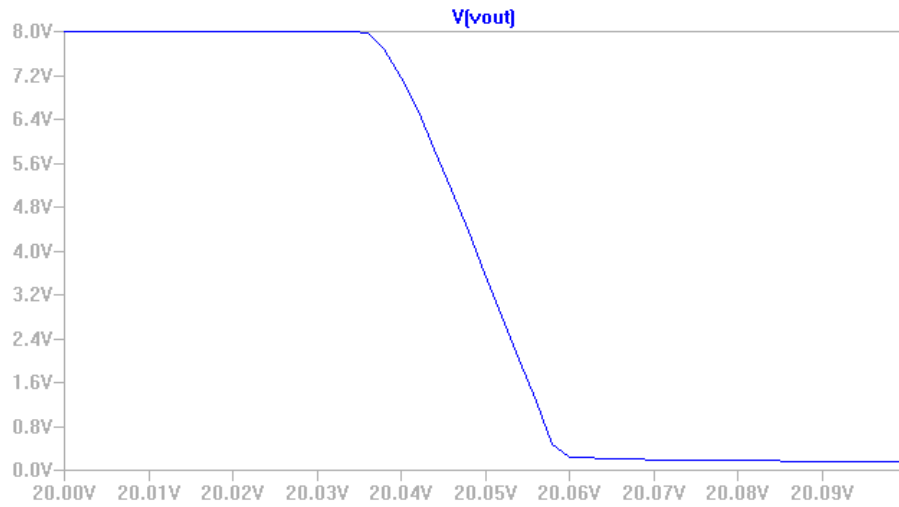


Figure 26: Feedback transfer function

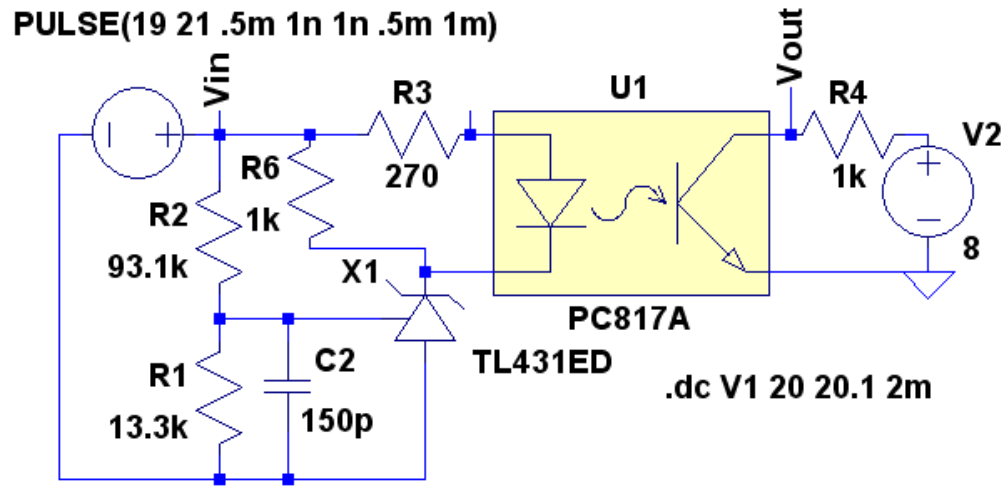


Figure 27: Feedback schematic

The isolated power supply was constructed but failed to perform properly. The output voltage would reach 150Vdc.

User Interface Design

The goal of this project is to create a working audio amplifier that people would be able to use in their home and requires an intuitive user interface. For this project I would like a minimalistic design which would reduce confusion and help the user operate the amplifier easily. At the very least the amplifier will need the following:

- Volume control
- Power on/off
- mute
- input selection

To increase the functionality without cluttering the amplifier with buttons and knobs I decided to incorporate a graphical LCD display which will be controlled by a microcontroller. The microcontroller will add a great deal of flexibility to the design because once the microcontroller is successfully integrated to the amplifier, the user inputs can be changed without any adverse effects to the rest of the system.

The microcontroller that will be used is an Arduino Uno because of its ease of use, and because it will be able to perform all of the required functions.

The volume control will be a resistor divider which can be adjusted to lower the volume from the incoming voltage level. This will be implemented using a digital potentiometer that incorporates four potentiometers and has memory so that the volume level will be remembered even after power has been turned off. The digital potentiometer will be controlled using a rotary encoder which the Arduino will monitor when the knob is turned.

There will be two audio inputs for each of the left and right speaker channels. There will be phono jacks used as one set of unbalanced inputs, and there will be XLR/ 1/4" TRS combination jacks used as a set of balanced inputs.

The display is a DOGM128 graphical display manufactured by Electronic Assembly. The graphical display operates over a serial interface with the Arduino which will require less pins compared to a parallel interface. The display provides the user with a menu driven interface that allows them to configure the amplifier quickly and easily. The display operates on +3.3V so all the control signals are put through a CD4050 buffer whose supply rails are at 3.3V.

There are three main modes to the controller. The first is the idle state which is exactly as it sounds. The second state is volume adjusting mode. This is entered from the idle state by rotating the rotary encoder. In the volume adjusting mode turning the rotary encoder clockwise increases the volume, and rotating it counterclockwise decreases it. Because there are 255 steps to the digital potentiometer the knob would need to be turned many times. Each step of the rotary encoder is set to increase the volume by 10 steps, rather than one so it now only takes one revolution to get the full scale range. To allow fine tuning, if the rotary encoder is turned while it is pressed, the volume will increment or decrement by one step. To exit volume mode the encoder knob is pressed.

The other state is the configure amplifier state which is where the user can change the balance, how temperature is displayed and the clock. This mode is accessed by pressing the encoder button while in the idle state. This brings up the main menu which consists of four selections. They are: Balance, Clock, Temperature, and Exit. If balance is selected the user is prompted with a screen which displays the balance and allows the user to adjust it by turning the rotary encoder. Turning the knob counterclockwise lowers it to at most -10 which corresponds to the right channel muted. Turning the knob clockwise increases the balance to at most 10 which corresponds to the left channel muted. Anywhere between 0 and 10 the left channel volume is lowered proportionately, and anywhere between -10 and 0 the right channel volume is lowered proportionately. The temperature menu consists of a selection screen between Fahrenheit and Celsius and the user selects using the rotary encoder. To exit the configure amplifier state the user selects Exit and the amplifier switches to idle state. The temperature sensor is a DS18B20 which operates over a OneWire bus and transmits the temperature in 9 bit format.

All the settings are saved to the Arduino's EEPROM as they are changed. When the amplifier is powered on the Arduino loads the saved values so that the user doesn't have to do any configuration after each startup.

Testing

Each aspect of the input stage was designed and tested individually. The component to be tested was the temperature sensor. The temperature was measured and sent to a computer through the serial interface. The temperature sensor correctly measured the temperature and sent it to the computer.

The second component to test was the rotary encoder. A simple script was used to keep track of the encoders position and send it back to the computer. As the encoder was turned the computer would track the transitions which would allow it to keep track of the position. After each transition the current position was stored in EEPROM so that after losing power the Arduino would be able to keep track of the position.

The third component was the LCD display. This took several attempts to get working correctly because I reversed the pinout in the first trials. Once the display was properly set up a sample program was used to confirm that instructions could be sent to it. The menu system was slowly built until it properly functioned.

The final component to test was the digital potentiometer which was connected using an SPI interface. I was able to get the first channel to operate correctly but the second channel was unresponsive. I then figured out that the bit positions for the channels were not the LSB so I had to change the channel numbers I was assigning to.

Integration

Putting all the working components together was more difficult than I thought it would be. Many of the components would interfere with each other and cause the entire system to fail. The LCD required a small amount of time to write everything to the display, but since the digital potentiometer used interrupts the LCD would fail to be written to sometimes. The temperature sensor also needed time to properly send and convert the information that would fail if an interrupt occurred. The result was an LCD which would lock up soon after starting and become unusable. It was decided to remove the LCD and temperature sensor and just leave the volume control. This functioned properly because there weren't any conflicts between the devices.

Input Stage Design

The high efficiency audio amplifier will be able to accept balanced or unbalanced inputs. The amplifier portion of the project requires balanced inputs. To satisfy these constraints an input stage is required.

There will be a balanced/unbalanced to balanced converter circuit which will take the input signal and create a balanced signal which will be passed to the volume control circuitry. The converter will consist of Op Amp subtractors that will generate equal but opposite magnitudes to power the amplifier chips. The schematic of the balanced/unbalanced to balanced converter is shown in Figure 28. It is single ended meaning that it runs only off of a single supply voltage[16]. This helps to simplify design since the power supply for the amplifier can be used to run the converter as well. The converter consists of two subtractors which the input voltages are capacitively connected to. The subtractors are identical except for the inputs are juxtaposed so that the output of one is equal but opposite magnitude of the other subtractor. One feature of this circuit is that it has a very high common mode rejection ratio so that any noise that appears on the input will not be passed on to the amplifier.

The amplifier was simulated with 1kHz inputs shown in Figure 29 and 30. The response is very good and the AC analysis shows good response across the entire frequency range.

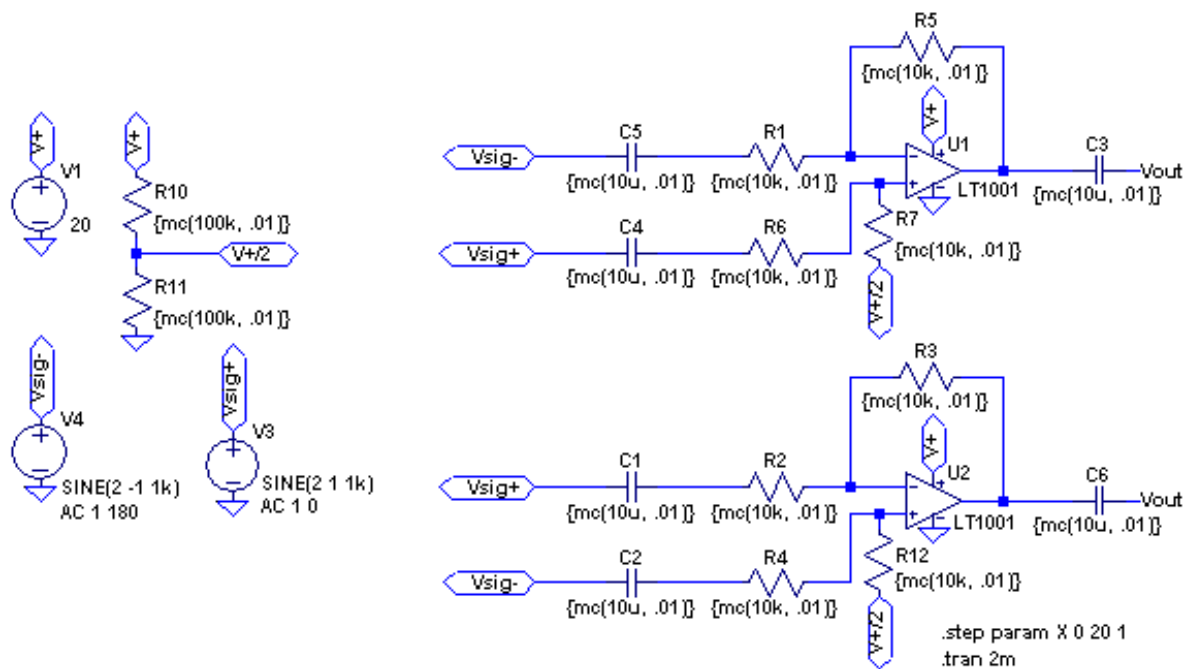


Figure 28: Schematic of balanced/unbalanced to balanced converter

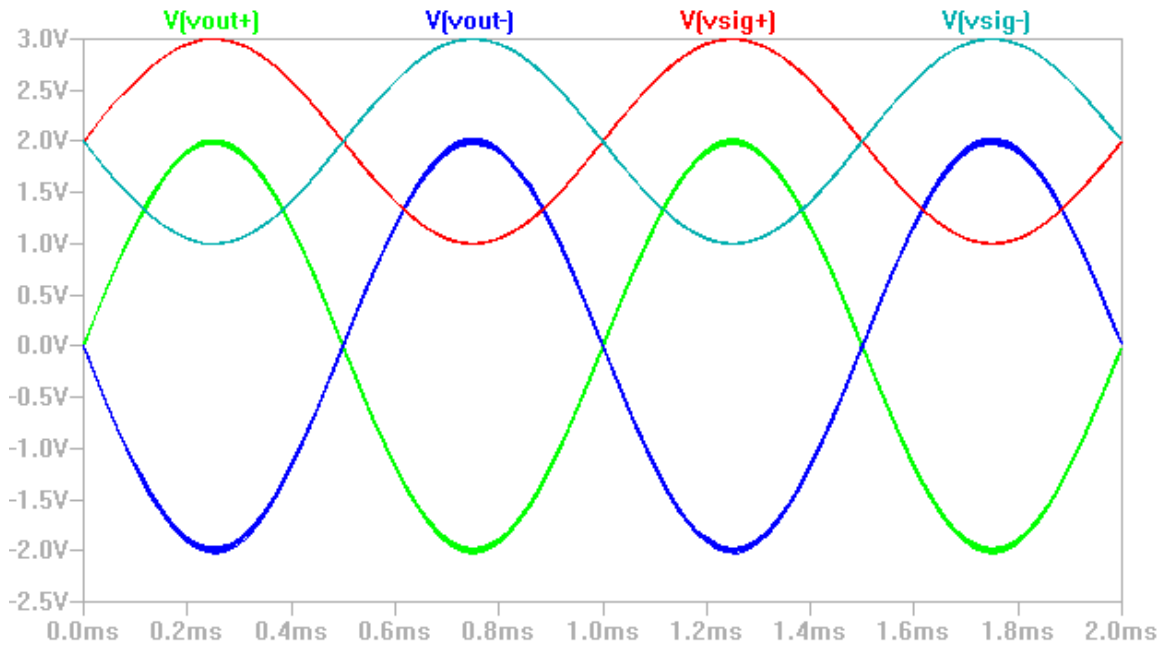


Figure 29: Output waveforms, vout+ and vout-, to the 1kHz inputs waveforms, vsig+ and vsig- in the converter

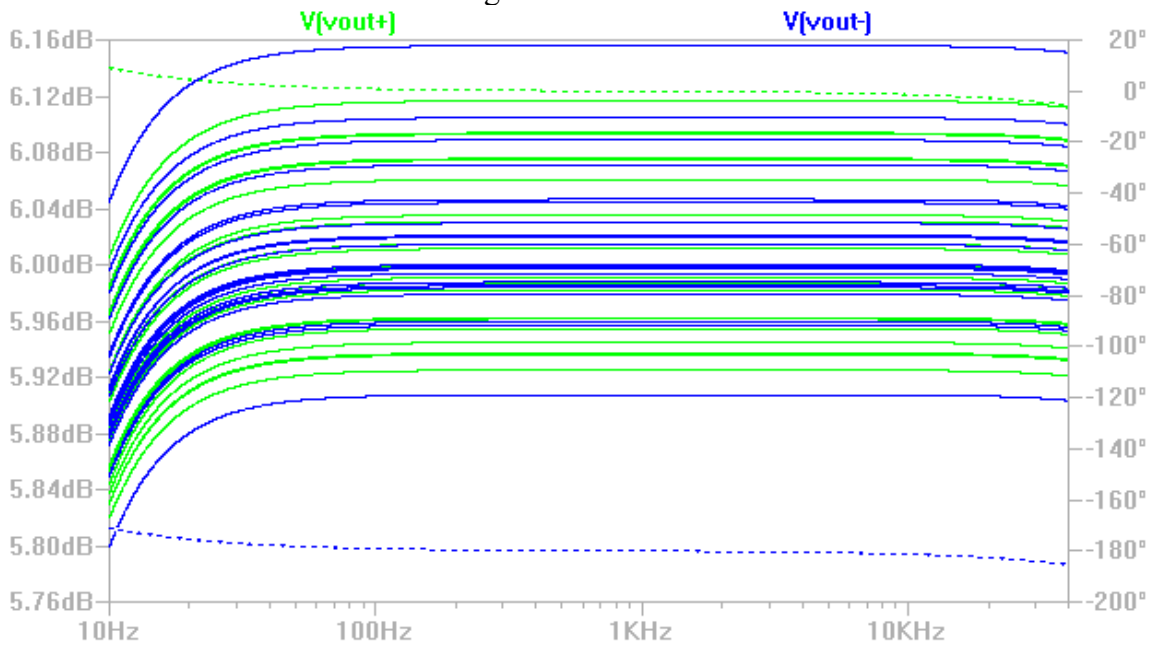


Figure 30: AC monte carlo analysis showing magnitude response within .35dB across 10Hz to 40kHz

The circuit was assembled and tested on a bread board. An oscilloscope was used to measure the output waveforms and a 4Vpp sine wave was applied across the inputs. This revealed a limitation with the circuit which makes it unsuitable for use with the amplifier. When it is used with unbalanced inputs who have a DC offset, the output waveforms have different magnitudes which is shown in Figure 31. The voltage across the outputs is the expected output, but with respect to ground they do not produce the correct outputs.

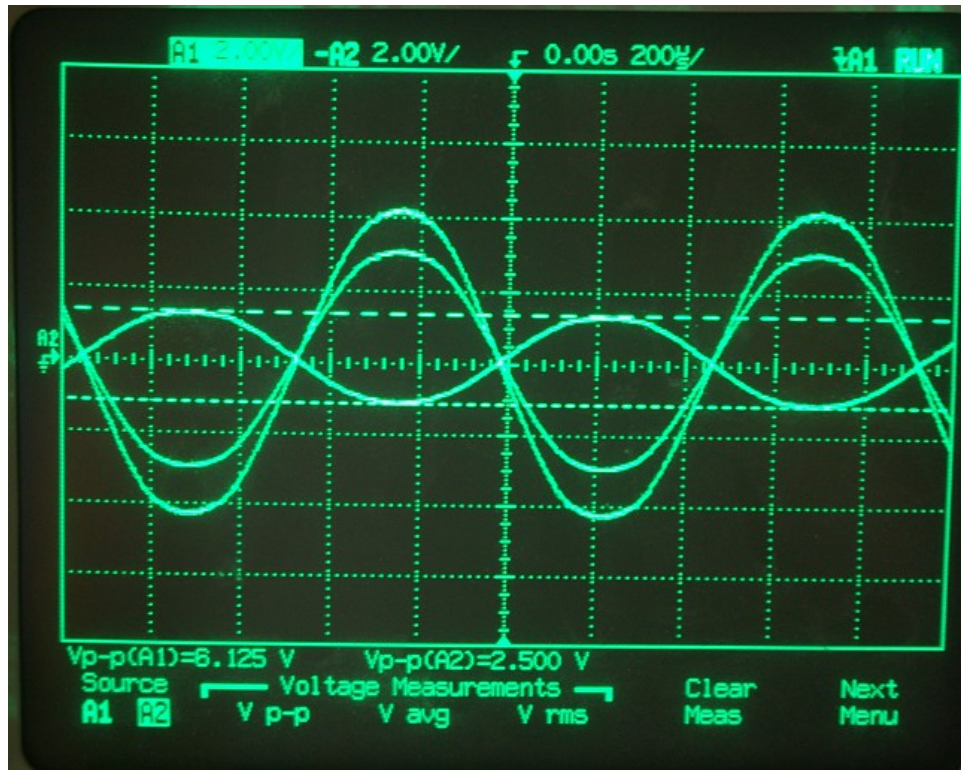


Figure 31: Output Waveforms showing out+, out-, and out+ - out-.

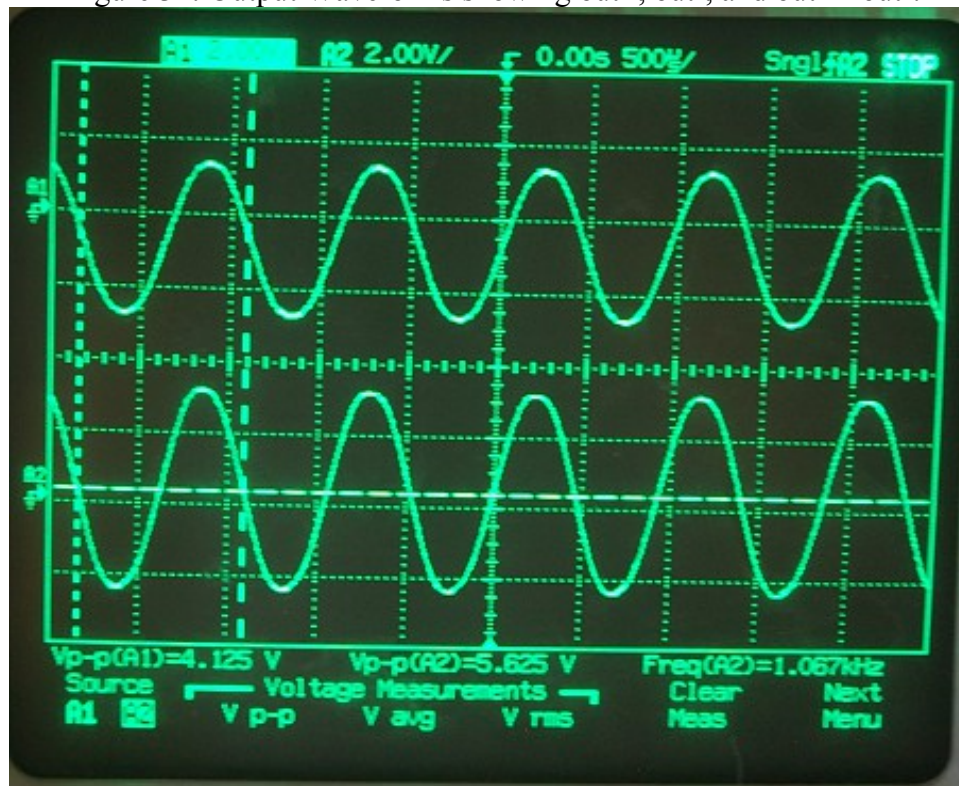


Figure 32: Input/output voltage waveforms measured

This brought up a big problem with the current design. If there was any DC offset then the subtractors would not output symmetrical waveforms. One would have a larger magnitude than the other and this would cause problems for the amplifier because the inputs need to have equal but opposite magnitudes.

To correct the problem the input stage was changed so that it followed the behavior of a balanced to unbalanced converter followed by an unbalanced to balanced converter. The difference in this design is that there is only one subtractor so the non-symmetrical outputs problem has been addressed. The inputs are subtracted from each other and then the inputs are buffered and inverted to get the balanced outputs. To control the volume a digital potentiometer is used after the subtractor so that only a dual potentiometer is required for the entire project. The revised input stage is shown in Figure 33 below[16].

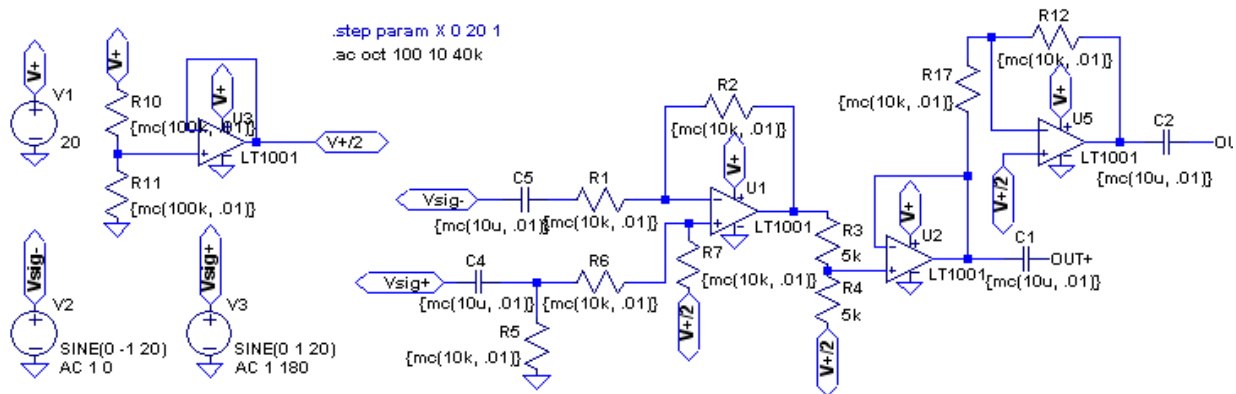


Figure 33: Revised input stage

There are several features that are important to this design:

- Virtual Ground
- Single Ended
- Input Impedance matched
- Digital Potentiometer

The single ended feature allows the input stage to be powered off of a single supply rail which allows for a much simpler power supply design. Because an op amp requires three voltage references the third source is generated using two 100kohm resistors as a voltage divider. That voltage is then buffered by a unity gain op amp and is referred to as the virtual ground because it is halfway between ground and the supply voltage. Since there is going to be a DC offset between the signal sources, they must be capacitively coupled. The coupling capacitors must be large enough because they act as a high pass filter, so they must be sized so the low frequency signals are not affected. The AC performance was simulated and shown in Figure 34 below.

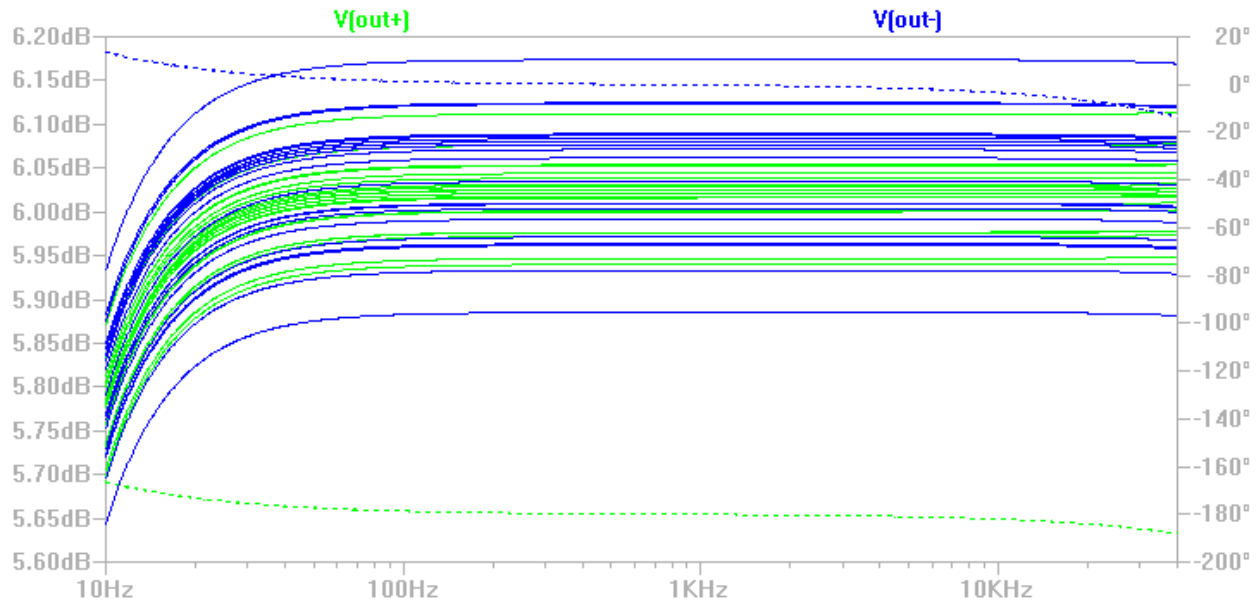


Figure 34: AC performance of the input stage

The Input Impedance matched means that both voltage sources will see similar loads so if any loading occurs both sources will be loaded equally. This is especially important when it comes to noise. With a low enough input impedance any noise will be filtered out because it cannot maintain the current required. The input impedance of the subtractor is different for each voltage source. To equal the input impedance a shunt resistor is added after the capacitor which reduces the input impedance of the positive leg to match the input impedance of the negative leg at 6.66kohm. The input impedance is measured across the audio frequency range using Monte Carlo analysis to account for tolerances and is shown in Figure 35 below.

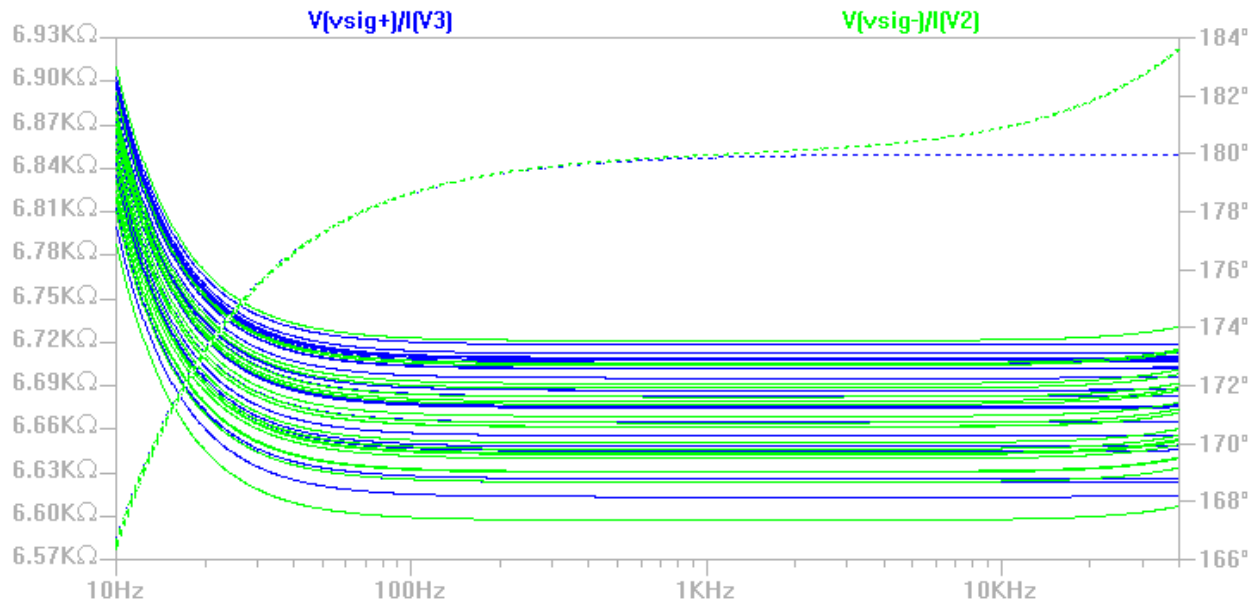


Figure 35: Input Impedance of the input stage.

The digital potentiometer is used to control the volume of the amplifier by acting as a voltage divider and lowering the voltage of the input signal.

The buttons that the amplifier will use to give the user the ability to navigate and make selections in the menus will be a combination of the rotary encoder and four small momentary push buttons. These will be generic inputs that whose function will change depending of which menu the user is currently in which will reduce the overall button

and IO requirement from the amplifier. The rotary encoder contains a push button that will also be used as part of the user interface.

The temperature sensor that will be used is the DS18B20 made by Maxim. It uses a oneWire interface so it requires only a single data line which reduces the overall IO requirements of the Arduino.

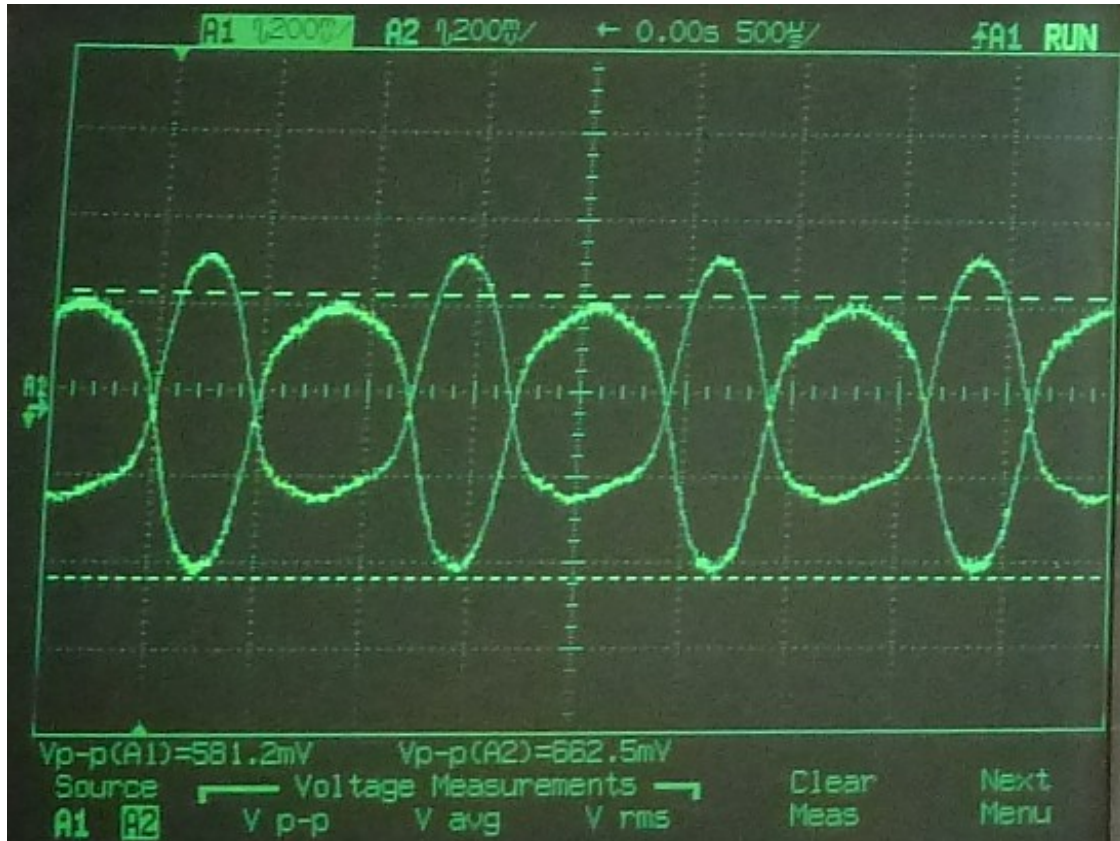


Figure 36: Outputs of the input stage showing severe clipping of the sinusoid

The assembled input stage was tested with the digital potentiometer removed and a wire jumper in its place. The output waveforms were measured using an oscilloscope from an input sine wave from a function generator. The output waveform is shown in Figure 37 below. The outputs of the input stage matched simulations very well, with the outputs in disagreement by only a few millivolts. The digital potentiometer was then put into the circuit and an Arduino board was used to control its resistance. The outputs now were very distorted as shown in Figure 36 above. The problem was that I didn't understand the operation of digital potentiometers and they have a maximum input voltage. The digital potentiometer is operating on a +5V rail which is the rated maximum voltage, but the rest of the circuit is operating on +20V rail. The inputs signal was centered around 10V so the output of the digital potentiometer was saturating. A coupling capacitor was placed in between the input of the digital pot and the output of the op amp. This had the effect of centering the signal such that the peak voltage was at the saturation voltage of the digital potentiometer. When the digital potentiometer was set for no attenuation this worked fine, but when attenuation was set the peaks were clipped and presented a large amount of distortion.

For the amplifier to output a 15Wrms sine wave, the maximum voltage needed on the input of the amplifier is 1.549Vpp because:

$$15W = V_{rms}^2 / 8\Omega$$

$$V_{rms} = \sqrt{120} = 10.95$$

$$V_{pp} = 2\sqrt{2} V_{rms} = 30.98$$

The amplifier has its internal gain set to 20dB which is a gain of 10. Since the output to the amplifier is balanced the required voltage is halved. The final peak to peak voltage required to achieve 15W output is 1.549V.

The input voltage to the entire input stage was lowered to 5V and this has cured the problem. The output waveform is shown in Figure 37 below which the attenuation set to 50%.

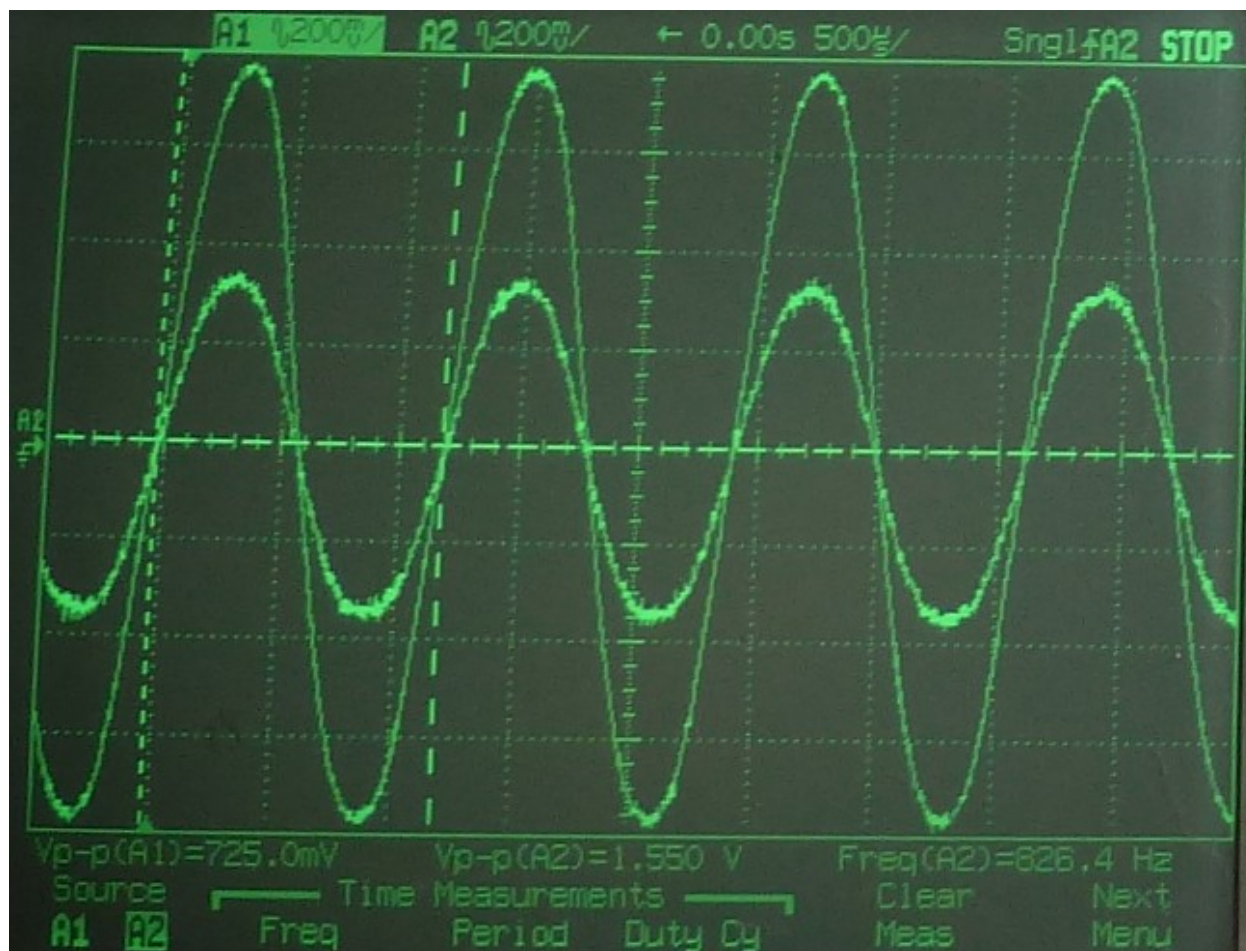


Figure 37: output waveform showing no distortion when attenuated 50%.

The input was sinusoidal was set to 1Vpp at 1kHz. The digital potentiometer was stepped from 0 to 250 step and the outputs were measured using an oscilloscope. The attenuation vs. step of each output is shown in Figure 38 below. The output error between the outputs of each channel is shown in Figure 39 below. The peak error is around 10% which corresponds to a .83dB error. The channel error was calculated by adding the output voltage of the outputs of each channel and subtracting them from each other and shown in Figure 40 below. The error is at most 9% but quickly falls to below 3% corresponding to a .265dB channel mismatch.

Some improvements that could be made to the input stage would be to add trimmer potentiometers so that the gain of each output could be adjusted until they were equal. This could be implemented by using a 9.1kohm + a 2.5kohm trimmer potentiometer in the feedback loop so that the gain could be set to the same as the complementary output which has a 10kohm resistor in its feedback loop. A digital potentiometer with a logarithmic taper would be much better for this project since people perceive loudness in a logarithmic fashion. The digital potentiometer has a large tolerance so using a topology that minimizes the error imposed by it would help consistency.

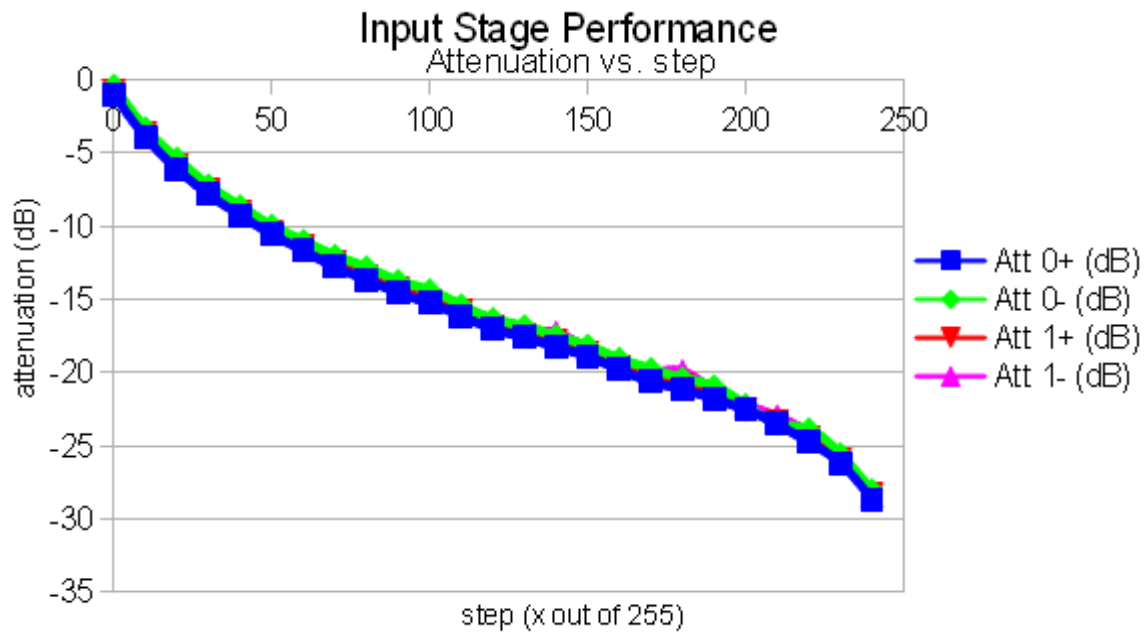


Figure 38: Attenuation vs. step for each output

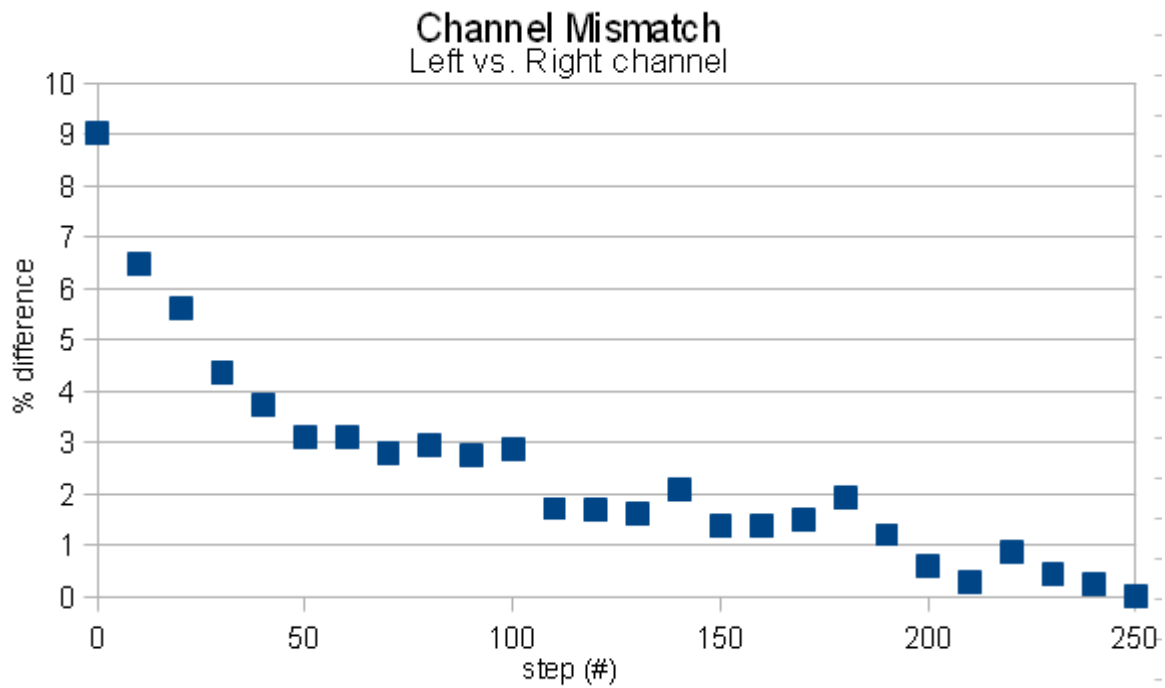


Figure 39: Difference in outputs for same step

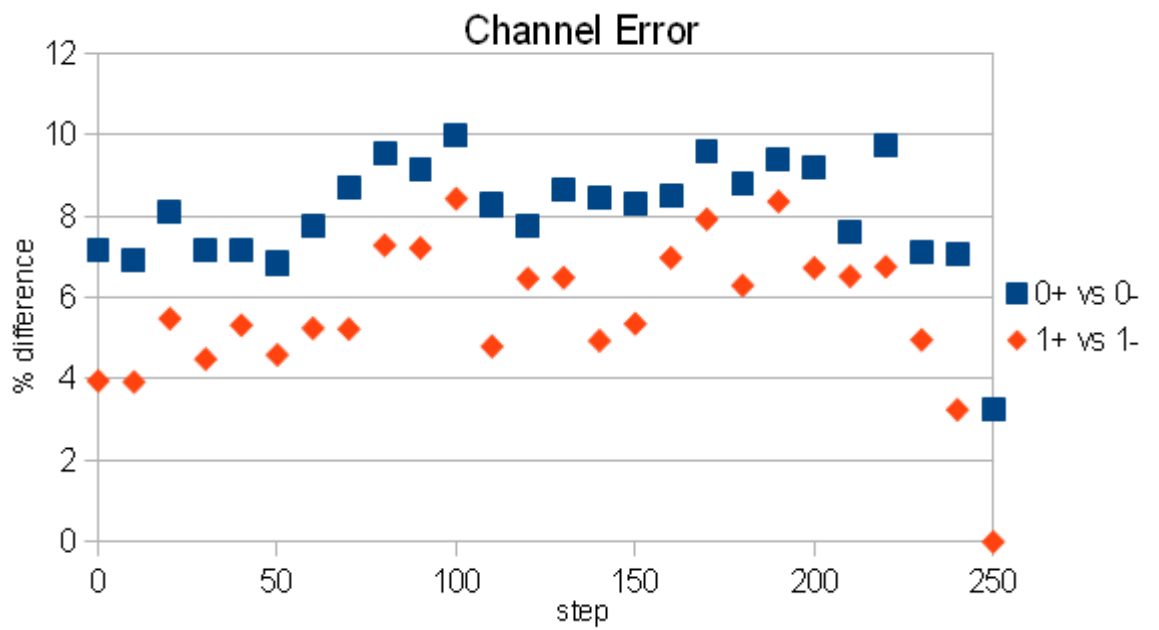


Figure 40: Mismatch between outputs of each channel

Amplifier Design

The amplifier portion of this project is designed around the IRS2092 integrated circuit which combines many of the critical components into a single package. To get an idea of how the circuit would operate a general H-bridge was simulated, and a pulse width modulated signal was generated using ideal voltage sources. The schematic of the circuit used is shown in Figure 41 and 42. Figure 41 shows the voltage sources used to generate the PWM. Four individual voltage sources are set up throughout the circuit to drive each MOSFET individually, and they all operate based on a comparison of the reference sine and triangle voltages. Figure 42 shows the load and the output filter which is used to eliminate the switching noise and smooth the output. The circuit was simulated for various loads and input voltages to see what voltages would be able to drive certain loads at the power levels required in the project[6],[17].

The first step is to build the reference design for the circuit just to get the circuit working. The reference circuit is shown in Figure 43. It is essentially a half-bridge inverter, so once it is working, a second will be required so that the amplifier can be operated from a single source in full bridge configuration.

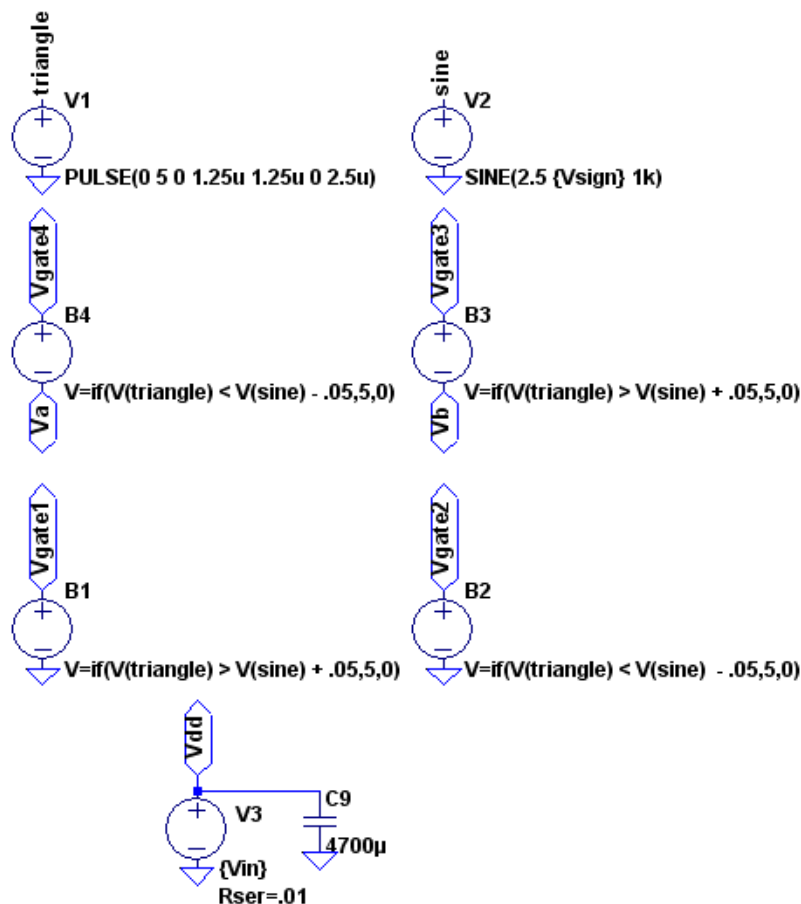
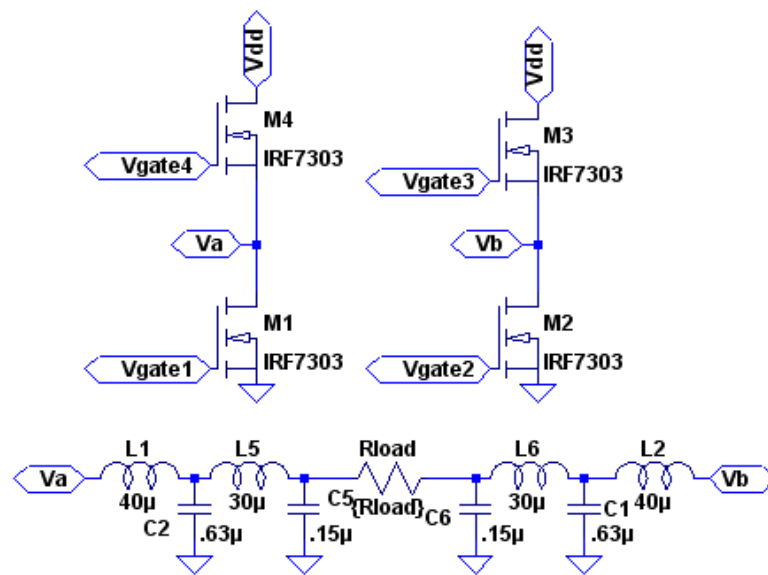


Figure 41: Circuit Used to create PWM signals to drive H-bridge



```
.tran 0 2m 1m 2u
.STEP PARAM Vin 8 24 16
.STEP PARAM Vsign LIST .1 .25 .5 1 2.5
.MEAS TRAN pin AVG -1*V(vdd)*I(V3)
.MEAS TRAN iinav AVG -1*I(V3)
.MEAS TRAN pout AVG I(Rload)*(V(n004)-V(n005))+I(Rload2)*(V(n001)-V(n002))
.MEAS TRAN iinpk max -1*I(V3)
```

Figure 42: Circuit used to simulate H-bridge for various input voltages and loads

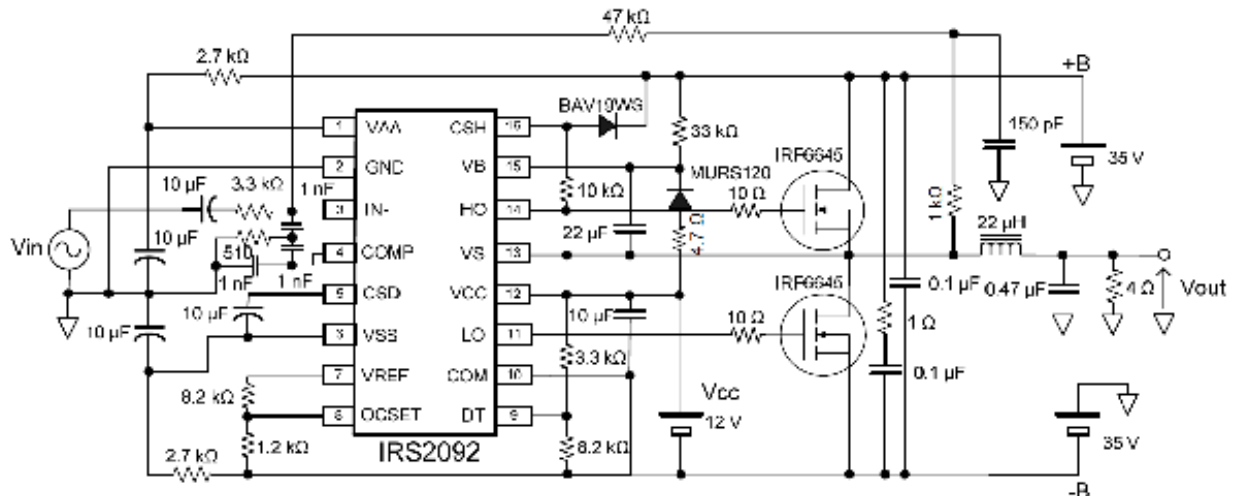


Figure 43: Reference circuit for IRS2092

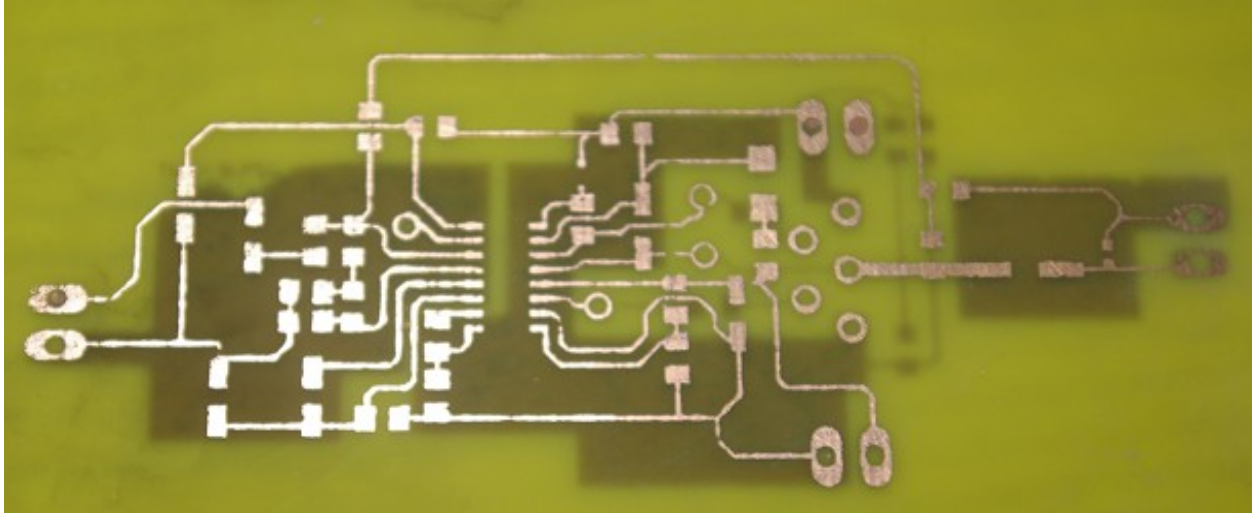


Figure 44: Etched PCB for amplifier using circuit shown in Figure 43. (top side)

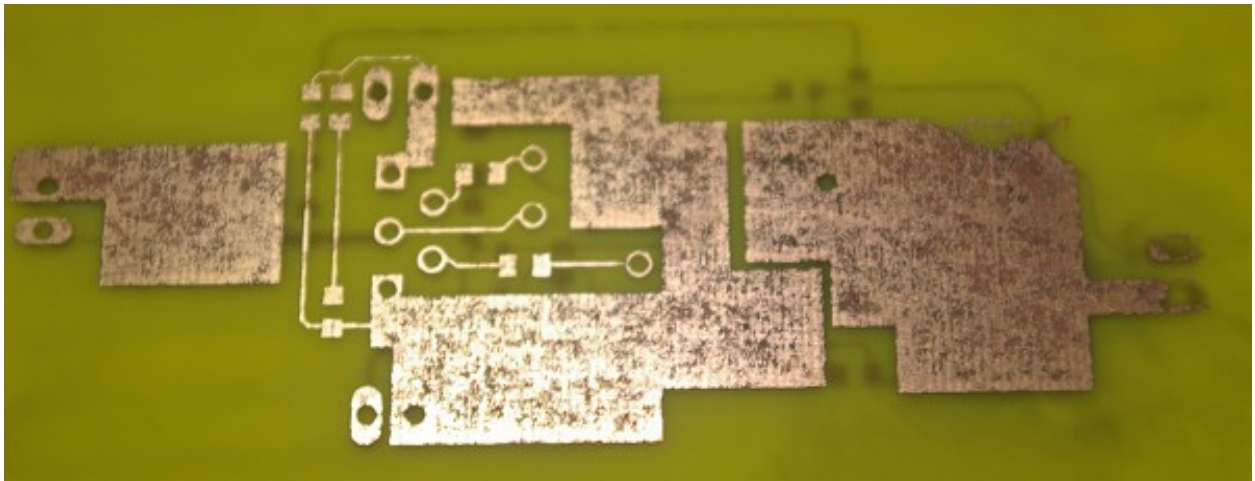


Figure 45: Etched PCB for amplifier using circuit shown in Figure 43. (bottom side)

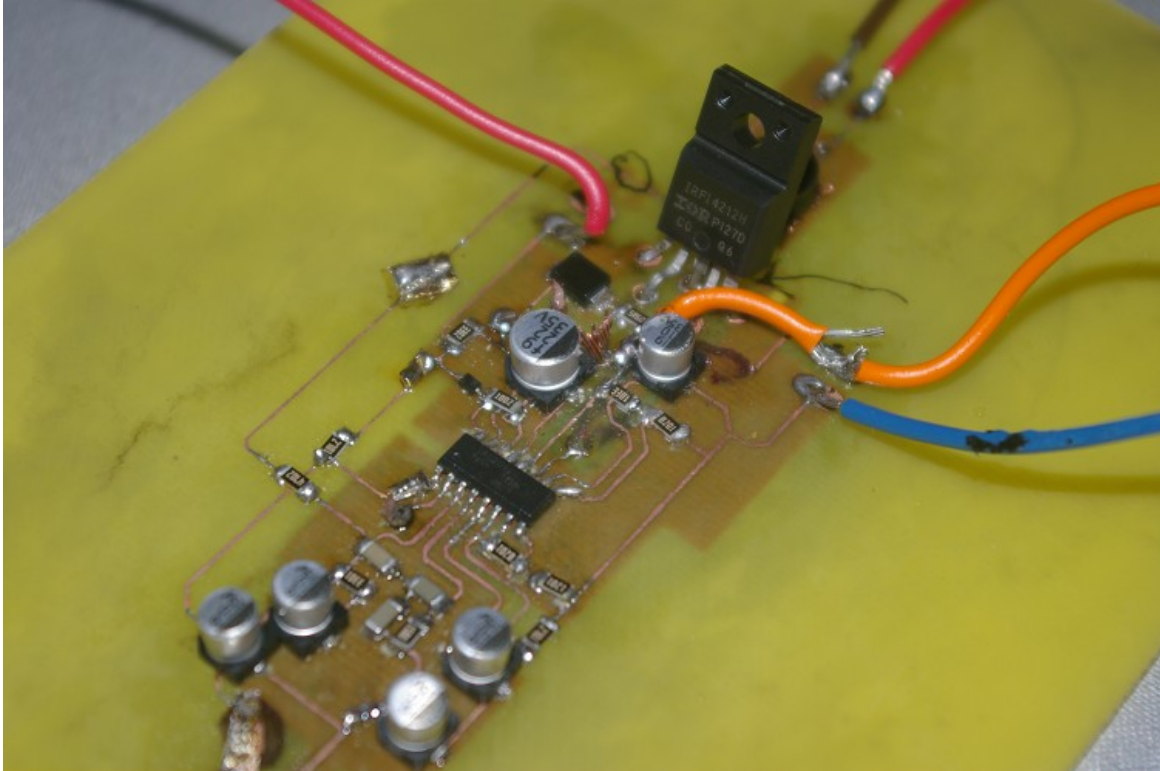


Figure 46: Assembled amplifier test circuit (top side).

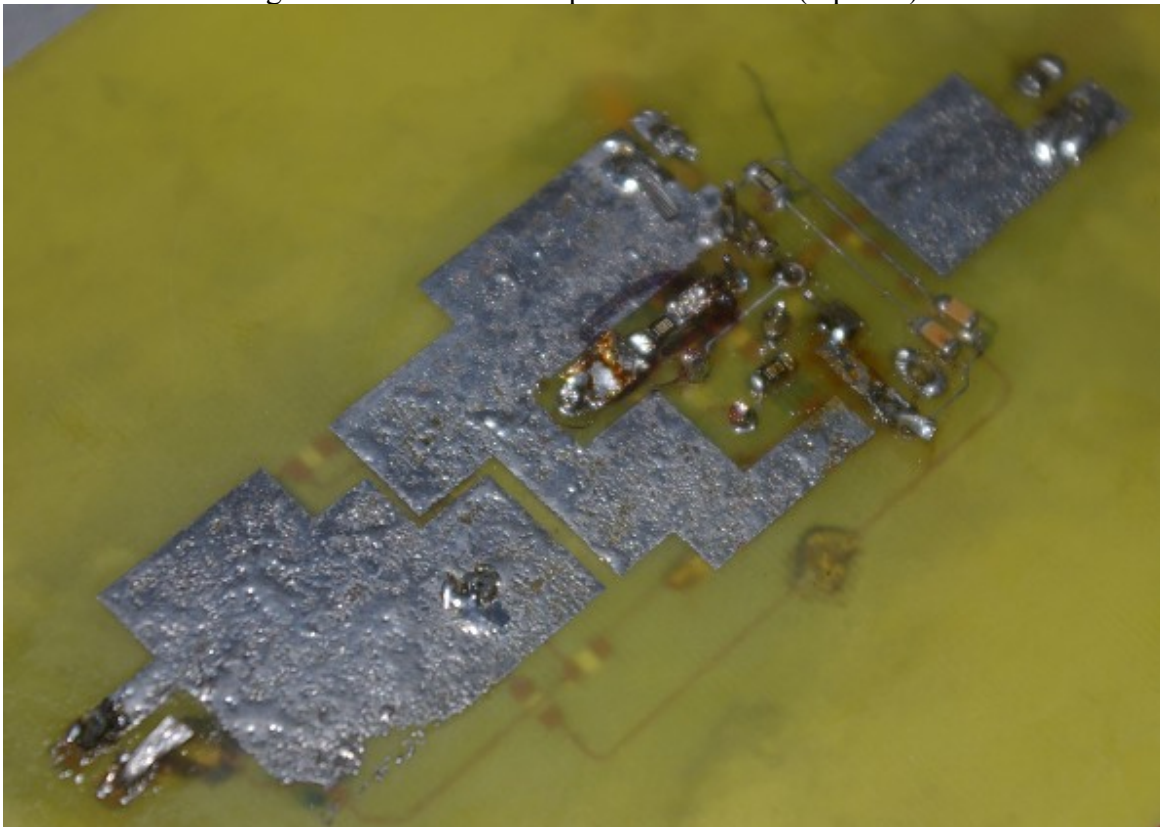


Figure 47: Assembled amplifier test circuit (bottom side).

I was never able to get the amplifier based around the IRS2092 to work correctly. The reference circuit was created for independent trials but each failed in the same manner. Upon powering up with the recommended supply voltages the half-bridge would shoot through and both FETs would turn on at the same time. This would pull tremendous current and the wires connecting the amplifier to the power supply would become hot and melt the insulation and any surrounding plastic.

I decided that the best way to proceed with the project would be to change the amplifier chip. Incorporating the switching FETs in the chip would simplify the design and have a much better chance for success. After looking into all the available amplifier chips three were chosen for serious consideration: TPA3125, TPA3106, and TFA9810. The characteristics of each chip are shown in Table something below[18].

The TPA3125 was chosen because it is the simplest of the three but is able to meet all of the requirements of the design. It is able to operate in both single ended stereo or bridged mono at higher output power. A single operating in stereo mode cannot deliver enough power to meet specifications, but in bridge configuration it will work. The reference design for a bridged output was made using all the recommended component values. The board was etched and soldered together shown in Figure 48 and 49 below. The amplifier worked properly but revealed a few problems with the design that need to be accounted for in the next revision.

- The amplifier was extremely susceptible to noise and interference. If the input leads were not connected to a source touching the wires or connecting oscilloscope probes would cause loud clicking and popping of the speakers.
- The input filter and output filters should be optimized for my particular application.

The noise problem arises from the fact that the amplifier had an extremely large input impedance. Most commercially available amplifiers have an input impedance around 10kohms. That is large enough for most sources that would be used with an amplifier, but any noise that is capacitive coupled will load it and the noise will disappear.

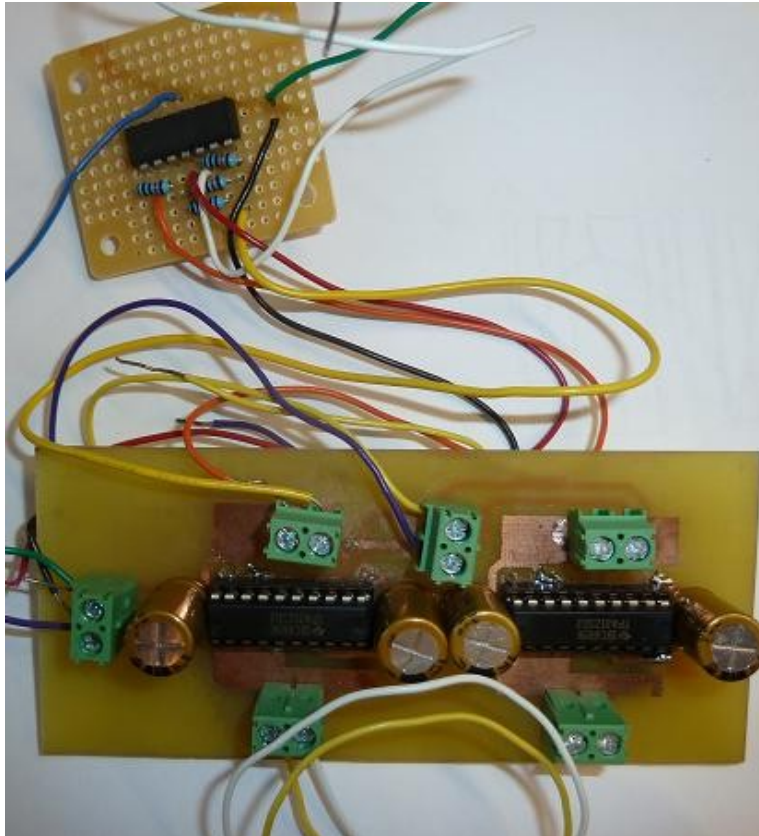


Figure 48: Top side of the assembled reference circuit for the TPA3125

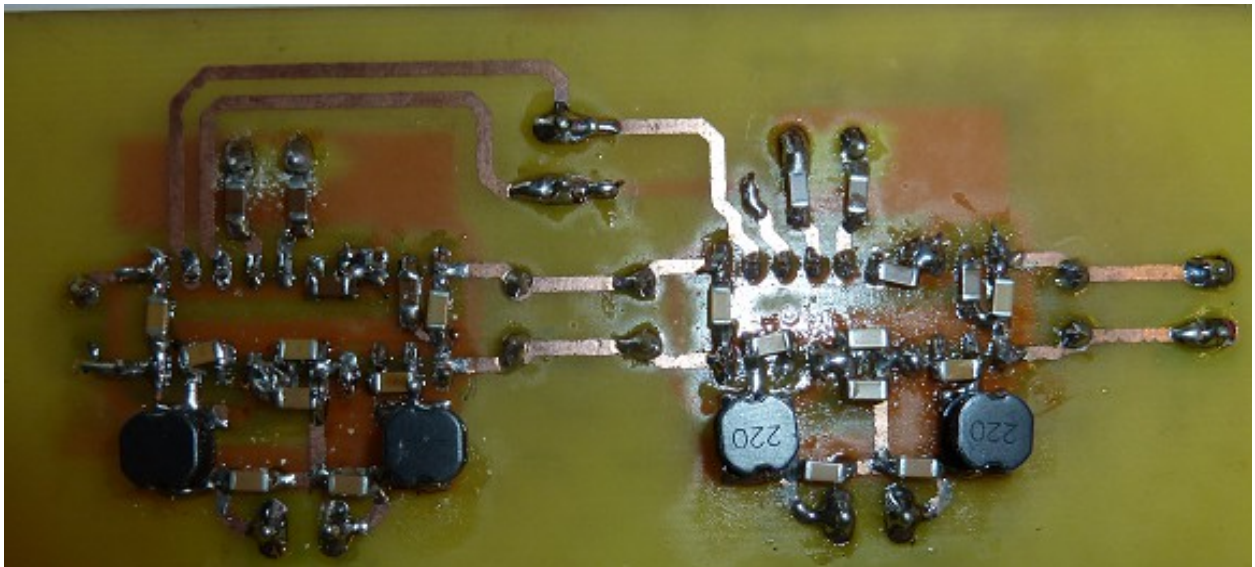


Figure 49: Bottom side of the assembled reference circuit for the TPA3125

The setup used to test the amplifier is shown in Figure 50 below. The amplifier was tested using a DC power supply set to 20V, and a function generator producing a 1kHz sine waveform. The load used was a power resistor box which would be set to 4 and 8 ohms. The current supplied to the amplifier was measured using a Fluke multimeter, and the output voltage was measured using an Agilent multimeter. Measurements were taken through the range of 15 watts output power and the data is shown in tables 2 and 3 below. The efficiency is plotted in Figure 51 below.

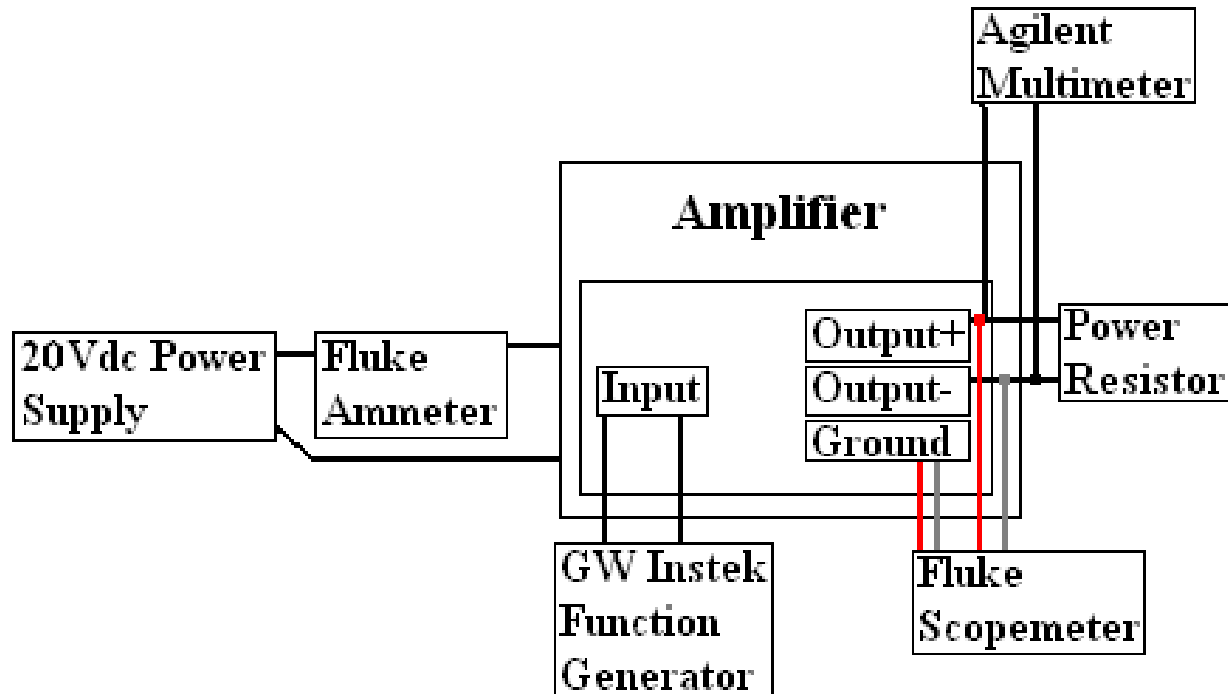


Figure 50: Test setup used to measure the performance of the amplifier.

I_{in} (Arms)	P_{in} (W)	V_{out} (Vrms)	P_{out} (W)	Efficiency (%)
0.07	1.34	0.76	0.14	10.63
0.07	1.48	1.01	0.26	17.23
0.09	1.80	1.42	0.50	27.78
0.12	2.43	2.00	1.00	40.95
0.19	3.71	2.82	1.99	53.61
0.32	6.34	4.02	4.04	63.76
0.58	11.62	5.64	7.95	68.46
0.75	14.95	6.36	10.13	67.74

Table 9: Amplifier performance driving a 4ohm load.

Iin (Arms)	Pin (W)	Vout (Vrms)	Pout (W)	Efficiency (%)
0.06	1.26	0.79	0.08	6.11
0.07	1.30	1.01	0.13	9.77
0.07	1.44	1.42	0.25	17.38
0.09	1.72	2.00	0.50	29.08
0.11	2.29	2.83	1.00	43.65
0.17	3.43	4.01	2.01	58.53
0.28	5.64	5.62	3.94	69.87
0.40	7.97	6.91	5.97	74.98
0.52	10.31	8.02	8.03	77.88
0.63	12.53	8.92	9.94	79.30
0.75	15.05	9.83	12.08	80.27
0.87	17.40	10.60	14.05	80.70
0.93	18.67	11.00	15.13	81.02

Table 10: Amplifier performance driving an 8ohm load.

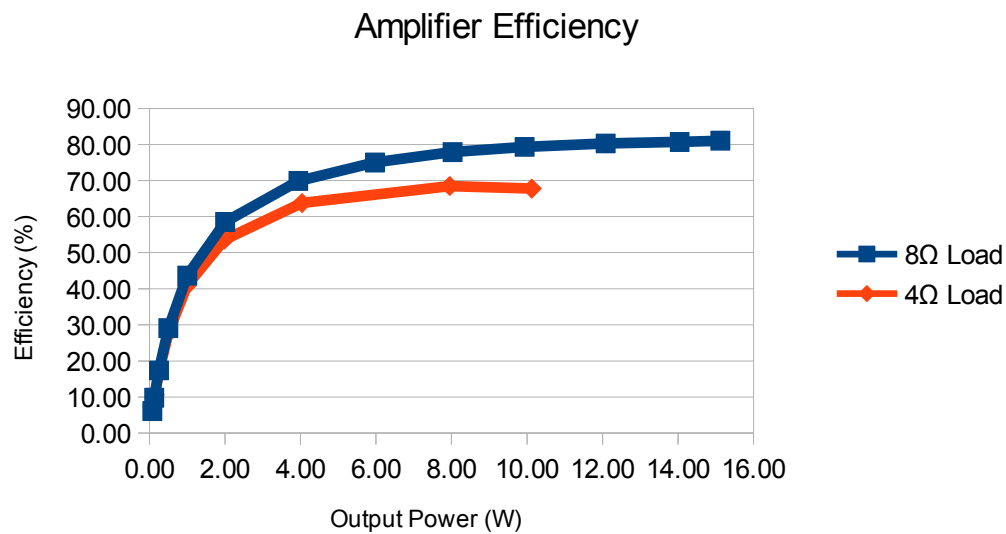


Figure 51: Efficiency vs. output power of the amplifier power 4 and 8 ohm loads.

The amplifier showed good performance because it was able to supply full power into an 8 ohm load. It was unable to do the same with a 4 ohm load because it would overheat and the chip would shut down. One way to increase performance would be to parallel two amplifiers which would increase available output power and efficiency at the expense of an increased parts count. Another thing that was troubling was the measured efficiency curve was about 10% lower than reported in the datasheet across the entire range.

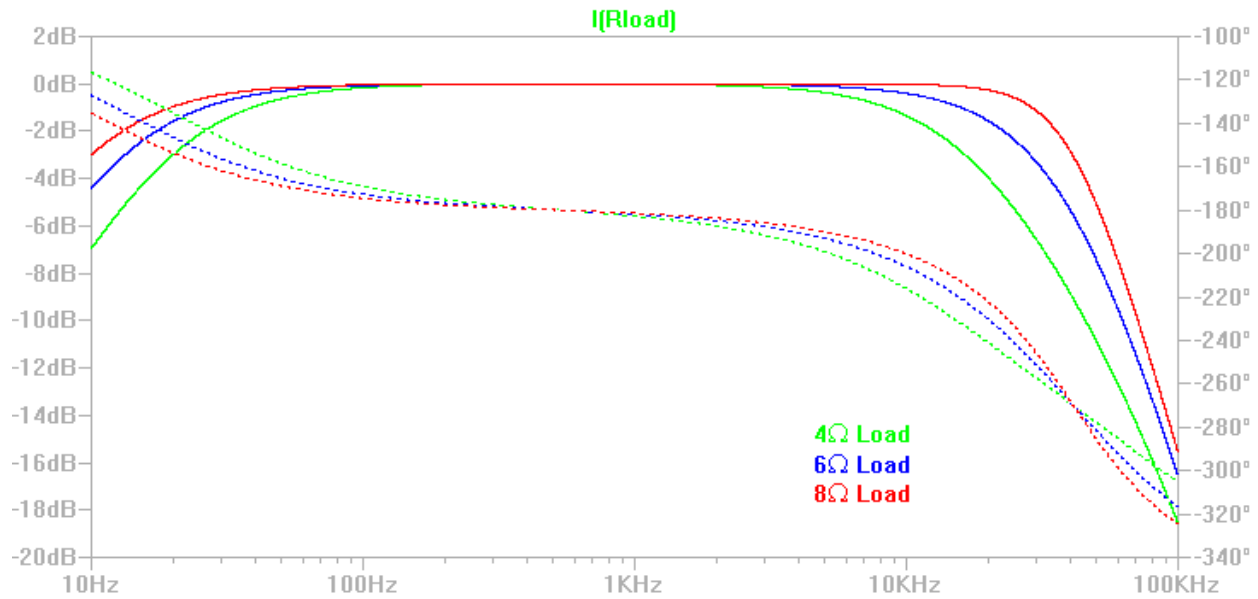


Figure 52: Output Filter Transfer Function

Lower -3dB Cutoff Frequency vs. Bypass Capacitor

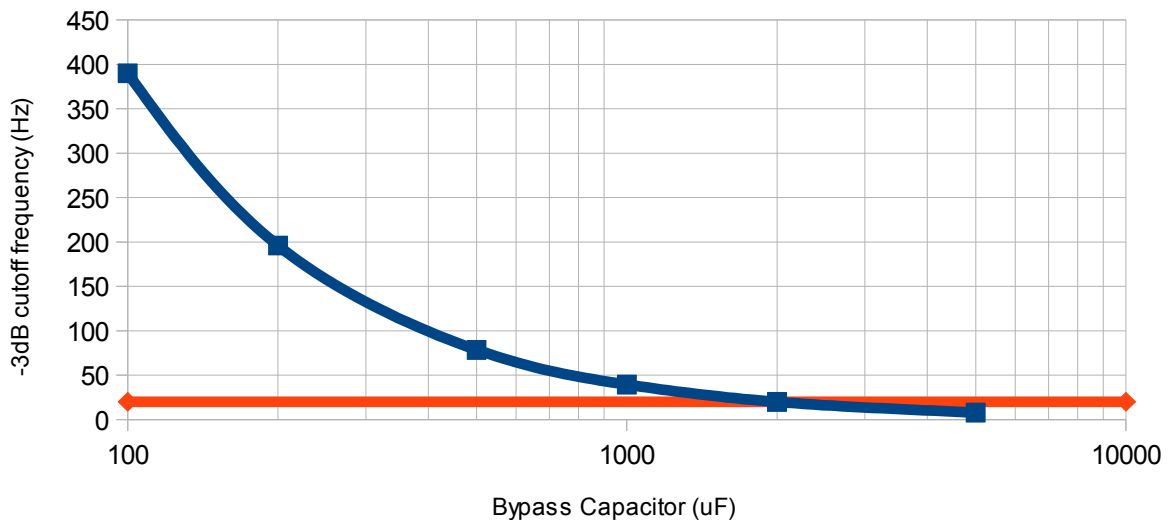


Figure 53: Simulation of the effect bypass capacitor has on amplifier performance.

The -3dB cutoff frequency caused by a bypass capacitor can be calculated by finding at which frequency the impedance of the capacitor equals the impedance of the load. The -3dB frequency occurs at much higher frequency with lower loads. Since this project needs to deliver response down to 20Hz the bypass capacitor needs to be large enough to have a -3dB response at 20Hz into a 4 ohm load. The minimum capacitor size is calculated to be 1989uF. Simulating with the rest of the filter confirms that this value performs as desired. The -3dB response was measured using a variety of capacitor sizes and is shown in Figure 53 below. Two 1000uF capacitors in parallel were used to create the bypass capacitor.

The project consists of two amplifiers, one for the left audio channel, and one for the right audio channel. The amplifiers' efficiency was measured for various loads and output powers. A function generator supplied a

sinusoidal input, and a DC power supply was used to power the entire amplifier. The load was a power resistor decade box which was adjusted to 4, 6, and 8 ohms. The input voltage, input current, output voltages, and output waveforms were measured using multimeters and an oscilloscope. The input waveform was adjusted from 0V to the voltage required to produce 15W output power.

The data for both amplifiers running together is shown in Table 11, 12, and 13 below. The amplifiers didn't turn on well as they would oscillate between on and off, or present a large amount of noise on the output. Eventually I was able to get them to stabilize but it should be noted that there was a tendency for them to become unstable and these measurements only reflect the performance when they worked correctly. For 8ohm and 6ohm loads the the efficiency increased rapidly from 0 to 15W output power, then continued to increase at a much slower rate. The efficiency topped out just below 90% for 8 and 6ohm loads, and the efficiency topped out around 81% for 4ohm loads.

The amplifiers were also tested individually and performed similarly as shown in Figure 55 and 56. The only difference between them is that the left channel was slightly more efficient across all loads, and significantly more efficient with a 6ohm load at low powers.

Individually tested, the amplifiers also showed significant distortions which depended on frequency and output power. Below 200Hz the output waveforms had a lot of distortion as shown in Figure 62. At 1kHz the amplifier would output a little distortion at low output power. As the output power was increased to around 1W the output became very distorted until around 4W output when the output became very clean. Around 3kHz and above 4W output the amplifier will sometimes vibrate audibly which is noticeable when driving dummy loads, but when driving speakers it isn't as noticeable.

8Ω Load 1kHz						
Vin (Vdc)	Iin (Arms)	Pin (W)	Vout0 (Vrms)	Vout1 (Vrms)	Pout (W)	Efficiency (%)
20.5	0.29	5.95	1.33	1.52	0.51	8.56
20.5	0.37	7.68	2.77	2.84	1.96	25.59
20.5	0.42	8.62	3.96	3.96	3.92	45.41
20.5	0.60	12.30	5.72	5.68	8.12	66.03
20.5	0.77	15.87	7.01	6.93	12.14	76.53
20.5	0.95	19.54	8.03	7.93	15.92	81.49
20.5	1.13	23.23	8.95	8.81	19.71	84.84
20.5	1.34	27.54	9.92	9.76	24.21	87.90
20.5	1.53	31.27	10.62	10.45	27.76	88.77
20.5	1.65	33.74	11.06	10.88	30.08	89.15

Table 11: amplifier performance with 8ohm load at 1kHz.

6Ω Load 1kHz						
Vin (Vdc)	Iin (Arms)	Pin (W)	Vout0 (Vrms)	Vout1 (Vrms)	Pout (W)	Efficiency (%)
20.5	0.30	6.05	1.31	1.43	0.63	10.41
20.5	0.37	7.60	2.82	2.83	2.66	35.02
20.5	0.42	8.52	3.54	3.51	4.14	48.58
20.5	0.60	12.32	4.97	4.90	8.12	65.90
20.5	0.79	16.25	6.02	5.92	11.88	73.07
20.5	0.98	20.15	6.92	6.80	15.69	77.85
20.5	1.19	24.36	7.80	7.65	19.90	81.68
20.5	1.37	28.01	8.50	8.34	23.62	84.34
20.5	1.58	32.40	9.24	9.05	27.89	86.08
20.5	1.73	35.53	9.73	9.53	30.89	86.95

Table 12: amplifier performance with 6ohm load at 1kHz.

4Ω Load 1kHz						
Vin (Vdc)	Iin (Arms)	Pin (W)	Vout0 (Vrms)	Vout1 (Vrms)	Pout (W)	Efficiency (%)
20.5	0.27	5.49	1.28	1.31	0.84	15.31
20.5	0.64	13.08	4.18	4.08	8.53	65.23
20.5	0.85	17.47	4.96	4.83	11.99	68.66
20.5	1.10	22.49	5.90	5.74	16.93	75.28
20.5	1.29	26.47	6.46	6.28	20.28	76.63
20.5	1.51	30.90	7.04	6.84	24.08	77.94
20.5	1.73	35.51	7.57	7.35	27.83	78.37
20.5	1.70	34.89	7.66	7.43	28.48	81.64
20.5	1.82	37.26	7.91	7.67	30.35	81.45

Table 13: amplifier performance with 4 ohm load at 1kHz.

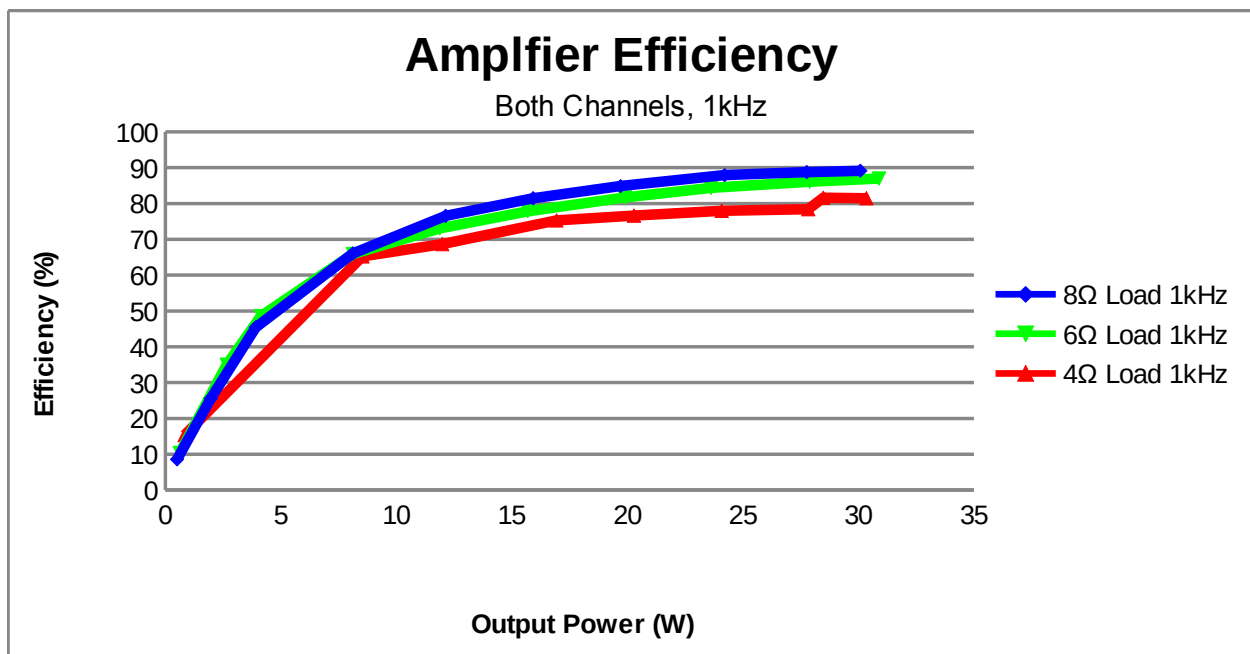


Figure 54: Amplifier efficiency vs. output power at 1kHz

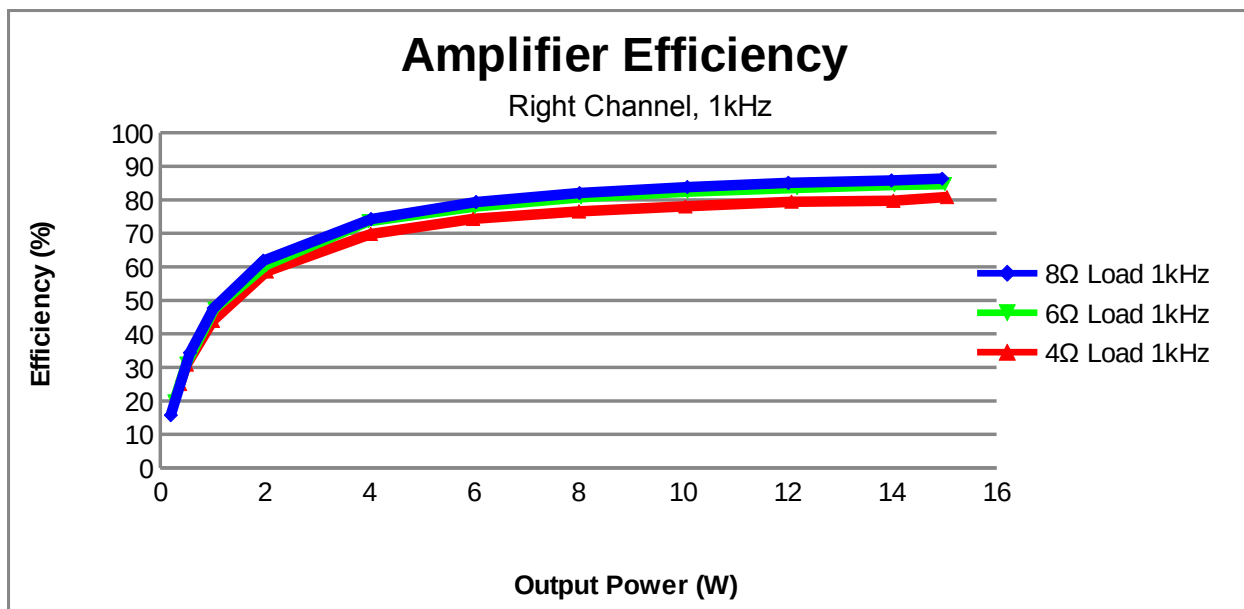


Figure 55: Right amplifier channel efficiency vs. output power at 1kHz.

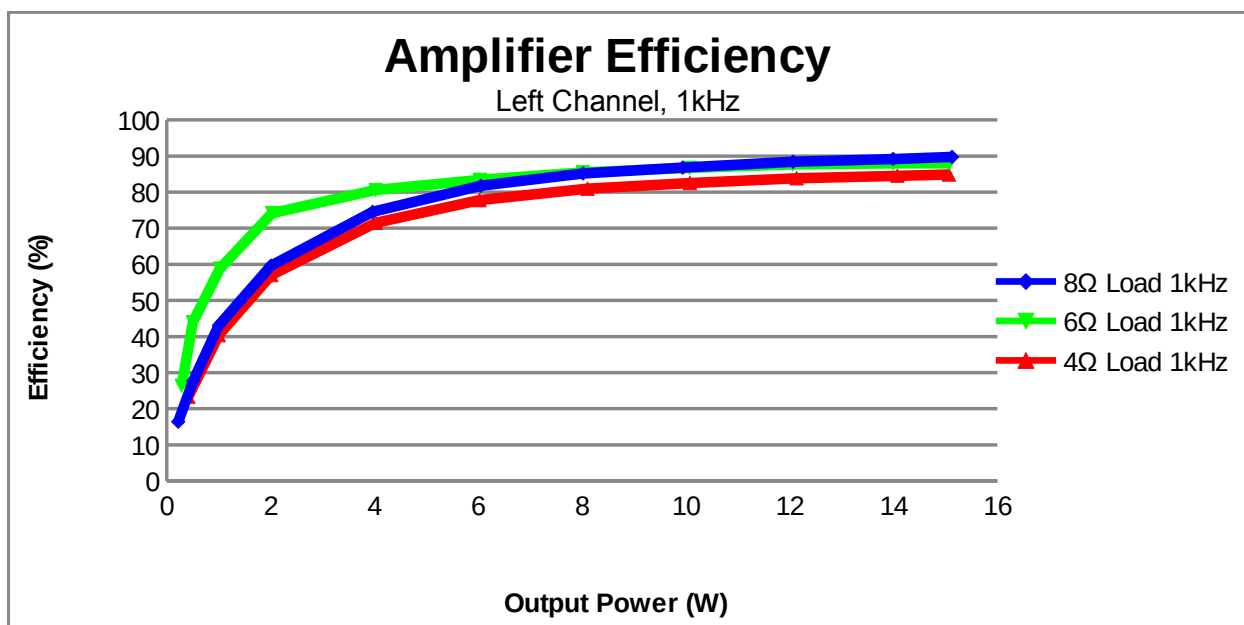


Figure 56: Left amplifier channel efficiency vs. output power at 1kHz.

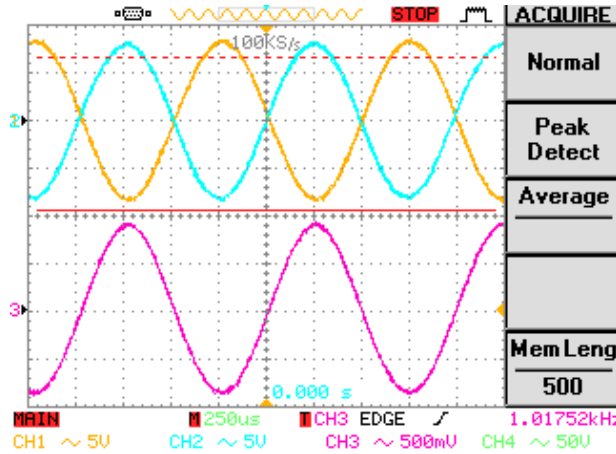


Figure 57: Both channels 30W, 8ohm, 1kHz

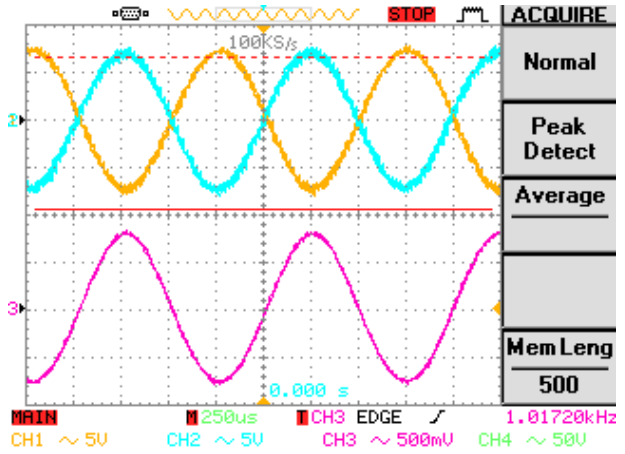


Figure 58: Both channels 30W, 6ohm, 1kHz

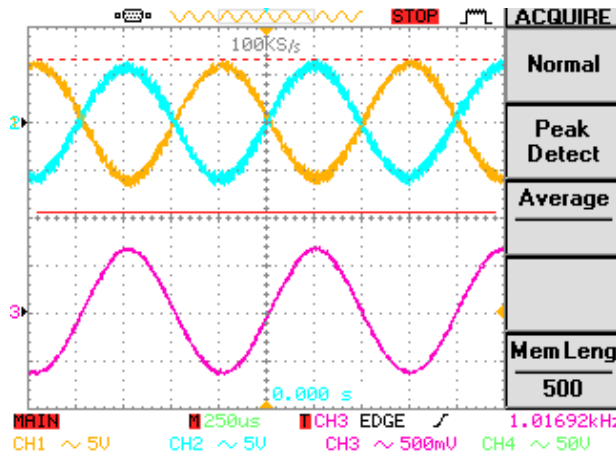


Figure 59: Both channels 30W, 4ohm, 1kHz

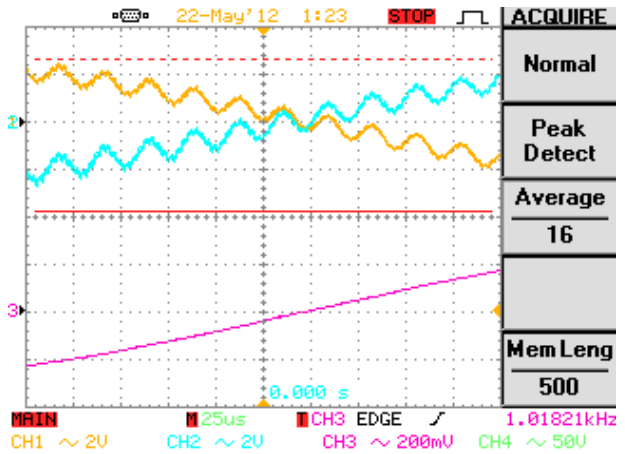


Figure 60: 40kHz noise

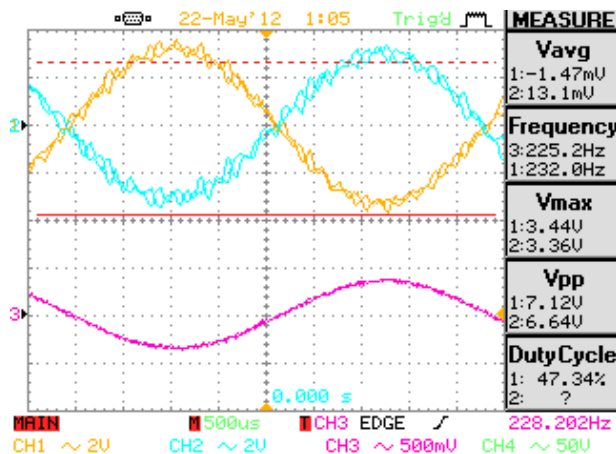


Figure 61: output at 230Hz

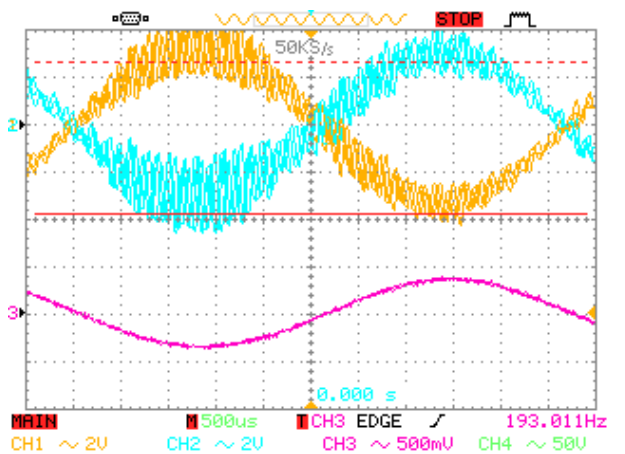


Figure 62: distortion at 200Hz

Suggestions for Improvement

This power supply is a good start, but there are several limitations that need to be addressed before it could be used in a consumer application. The main issue is that the output is not isolated from the input which presents a safety hazard. The output ground is directly connected to the neutral on the input so if something bad were to happen on one end, that problem would be present on the other end. If the hot and neutral were reversed in the receptacle that powers the amplifier it would still function properly, but 120Vac would be present on the ground which can pose a major shock hazard. If I were to do this project again I would design it isolated using either an optocoupler or an auxiliary winding to provide feedback to the controller. The second limitation of the power supply is that it has a large output voltage ripple. I would recommend changing PWM controllers from the LTC3803 to a more common arrangement of UC3842 + TL431 because they are much cheaper and widely used.

The flyback converter was a good choice to begin designing with because it is relatively simple, but its performance isn't as good as some other topologies, and in audio applications this can be unacceptable.

The amplifier portion meets all its specs as is but could use refinement. The main issue is that it uses four IC each capable of stereo output to provide stereo output. There are four times as many chips as necessary which just about quadruples the cost since all the supporting circuitry is doubled as well. The ideal solution would be to move to an IRS2092 based amplifier because that gives a much more customizable solution to get the best performance for the given application.

The input stage works adequately but an easy way to improve the functionality without adding a lot to the cost would be to add DSP to the amplifier. This would eliminate the need for the digital potentiometer and give the designer the option to add many features such as tone controls, digital inputs, and digital outputs. The Arduino board is not suitable for a final product so an Atmega328 dip package can be purchased and programmed using an Arduino board, and the micro-controller used in this project. It would reduce a significant amount of the cost and bring the project closer to being consumer ready.

Enclosure Design

The enclosure is what will house all of the components of the high efficiency audio amplifier. Since I have access to a wood shop I chose to make it out of wood due reduce the cost for me to manufacture it. The Power switch is a single pole double throw rocker switch that switches the incoming hot, and the shutdown signal of the amplifier. The mute switch is a single pole single throw toggle switch that connects the mute signal of the amplifier to ground. There are two sets of inputs on the back of the enclosure. One set is a pair of RCA connectors which accept an unbalanced signal. The other set is a combination XLR/1/4" phone jack that accepts balanced or unbalanced inputs. Both sets of inputs are connected to a rotary switch that is 6 pole double throw. The output of the rotary switch connects to the input of the balanced to unbalanced converter. The outputs of the amplifier are 4 pole Speakon connectors with only two of the poles utilized. Speakon connectors were chosen because their price is similar to binding posts or other conventional connectors. They are also very rugged and easy to use since they are used in professional equipment and are designed to take abuse. The power input is a Powercon connector which is similar to a Speakon connector except it only has three poles and is designed to be used with mains electricity. It was chosen because it price was similar to other power entry modules but this is very rugged and is twist locking which adds to the safety factor. The assembled box is shown in Figure 63 and 64 below.



Figure 63: Front of enclosure showing switches and knobs

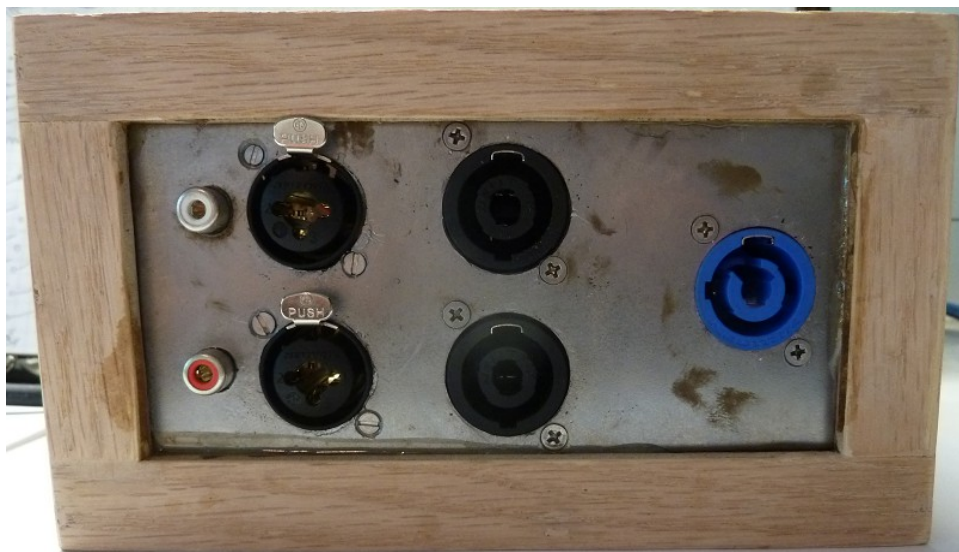


Figure 64: Back of enclosure showing inputs and outputs

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ABET Senior Project Analysis

Project Title: High Efficiency Audio Amplifier

Student's Name: Grant Moore

Advisor's Name: Dale Dolan

Summary of Functional Requirements

This amplifier will be able to achieve overall efficiencies of 70% or greater when providing more than 5watts of power to speakers ranging from 4 Ω to 8 Ω nominal impedance. It will be able to do this with less than .1% THD.

Primary Constraints

Anticipated difficulties include developing an adequate PCB because the amplifier and power supply will most likely use devices that turn on and off very rapidly (more than 1kHz). This can create many problems if the PCB is designed haphazardly, due to the effects of switching noise on the rest of the circuit. Another issue is circuit complexity. Most high efficiency amplifiers use more parts, which can add significant design time. To avoid this, portions of the amplifier which have a small impact on performance should be purchased such as gate drivers and micro-controllers. Other parts that have a key impact on the performance should be designed such as driver mosfets.

Economic

There are many economic impacts that this project will have. With greater efficiencies than conventional amplifiers less energy will be wasted to deliver the same listening experience to the consumer. This reduced energy consumption will result in a lower power bill for the consumer, which results in less profit to the utility due to less power sold. Since the utility is providing less power, less fuel will need to be purchased which affects those who transport the fuel to the plant, those who extract it from the earth, and those who are looking for new sources of fuel.

See gantt chart and cost estimates in the appendix.

If manufactured on a commercial basis

This would sell around 500 a year because there aren't a lot of people looking for new stereo setups, and the energy savings wouldn't justify replacing a lesser efficient amplifier because of the price. To sell more this amplifier could be incorporated into a multichannel home theater amplifier, which is what the majority of consumers are purchasing. The manufacturing cost of each amplifier can be broken into parts and labor. The parts cost will \$50 because mass production will greatly reduce the price of parts, and PCBs will be much cheaper. The labor cost will be around \$15 because it may take 1 hour for someone to assemble and solder everything. The sale price would be around \$130 because the manufacturer needs to make a profit, and the retailer needs to make a profit and 40% is a good estimate. The profit for the manufacturer is \$26 per unit sold, and at 500 units per year the profit is \$13000. The profit for the retailer is \$36.4 per unit sold, and at 500 units per year the profit is \$18,200. The cost of the consumer to operate the device for a year at 30 minutes per day and \$0.10 per kilowatthour, using 5 watts/channel at 70% efficiency is \$0.26. A conventional amplifier under the same conditions at 25% efficiency will cost \$0.73. By using the high efficiency amplifier customers can reduce their operating cost by two thirds which is insignificant a low usage levels.

Environmental

Since manufacturing the amplifier requires various electronic components, and a printed circuit board these are acquired by mining the earth for the resources needed such as copper, silicon, and aluminum. The mining process can have detrimental effects to the environment. The disposal of the amplifier will also have poor effects on the environment since it contains many parts that are dangerous to other species. The amplifier will require less power, which uses less power from the electric utility, which results in less natural resources being harvested to make power.

Manufacturability

This product will be able to be manufactured relatively easily since it is a PCB housed inside an enclosure. Many devices are already manufactured that are very similar to this. One aspect of this project that makes it easier to manufacture than other project is that it will not require as large of components as a similar amplifier would. Since it has higher efficiencies smaller components are used where a conventional amplifier would use large ones. This saves space during manufacturing and requires less money for parts.

Sustainability

There will be few parts to maintain in this amplifier because most of the parts will be solid state and last a very long time under normal conditions. The only parts that might need maintenance are the input and output jacks because they might corrode. If the amplifier is subjected to harsh conditions components may fail that will be very difficult for the consumer to diagnose and will not be cost effective to diagnose and repair.

Ethical

One ethical issue associated with this product is labor laws. Since labor will contribute a significant amount to the total manufacturing cost, cheaper labor will be an effective way to lower the cost of the product. But choosing labor based on lowest cost leads to many issues such as working conditions and worker abuse that will have detrimental effects towards those making the product.

Health and Safety

Since this amplifier will get power from a wall outlet, there is a chance that the consumer could shock themselves with mains voltage. Other hazard is hearing loss which can occur if the consumer listens at high volumes for long amounts of time that can cause permanent hearing loss.

Social and Political

The product main impacts the consumer because they will be using less power to get the same listening experience. The power company is also impacted but not in any noticeable way since the power savings isn't large when compared to other loads that they are supplying. The main parties that this project will benefit are the consumer, the manufacturer, and the parts provider. Those hurt by this product will be competing companies whose product might have been purchase had this one not been available.

Development

To properly complete this project I will need to combine knowledge from many different courses including power electronics, system programming, and Digital Electronics. A efficient way to build this project would be to use many available parts as possible so that I won't have to reinvent the wheel. This way more attention can be given to certain parts of the project without getting bogged down in other areas. The key to getting this project completed on time and meeting requirements will be to adhere to a schedule that. The first quarter of the senior project will be dedicated to developing and defining what the end product will be. By the beginning of the second quarter I should have a very good idea of how the project will be made and initial circuits designed. Once this initial circuits have been designed and tested the circuits will be redesigned and the process repeated. A single design cycle should take about three weeks to account for designing, ordering, building, and testing the project.

Appendex

Arduino Code

```
#include <Encoder.h>
#include <EEPROM.h>
#include <SPI.h>

#define MEM_VOLUME 1 //EEPROM Memory location for volume
#define MEM_BALANCE 2 //EEPROM Memory location for balance
#define DEBOUNCE_TIME 200 //Time to debounce button in milliseconds

#define ENCODER_PINS 5,6 //Digital pins that connect the encoder
#define BUTTON_PIN 7 //Digital pin that connects the encoder button
#define CS_PIN 10

Encoder myEnc(ENCODER_PINS);

boolean buttonPushed = false;
int lastDebouncedTime = 0;
int volume;
int leftVolume;
int rightVolume;
int balance;
long oldPosition;
long newPosition;

int volumes[24] = {255, 254, 253, 252, 251, 250, 240, 230, 220, 210, 190, 170, 150, 130, 110, 80, 70, 60, 50, 40, 30, 20, 10, 0};

void setup()
{
  pinMode(BUTTON_PIN, INPUT);
  pinMode(CS_PIN, OUTPUT);
  digitalWrite(BUTTON_PIN, HIGH); //Activate pull-up resistor
  volume = EEPROM.read(MEM_VOLUME);
  balance = EEPROM.read(MEM_BALANCE);
  oldPosition = -999;
  Serial.begin(9600);
  SPI.begin();
}

void loop()
{
  newPosition = myEnc.read();
  if (newPosition != oldPosition)
  {
    if(newPosition % 4 == 0)
    {
      if(newPosition - oldPosition > 0)
      {
        buttonPushed = digitalRead(BUTTON_PIN);
        if(!buttonPushed)
        {
          balance += 1;
        }
      }
    }
  }
}
```

```

        if(balance > 10)
        {
            balance = 10;
        }
    }
    else
    {
        volume += 1;
    }
    if(volume > 24)
    {
        volume = 24;
    }
}
else if(newPosition - oldPosition < 0)
{
    if(!buttonPushed)
    {
        balance -= 1;
        if(balance < -10)
        {
            balance = -10;
        }
    }
    else
    {
        volume -= 1;
    }
    if(volume < 0)
    {
        volume = 0;
    }
}
Serial.println(buttonPushed);
EEPROM.write(MEM_VOLUME, volume);
EEPROM.write(MEM_BALANCE, balance);
setVolume(volume, balance);
}
oldPosition = newPosition;
}
}

```

```

void setVolume(int volume, int balance)
{

    Serial.print("Balance: ");
    Serial.println(balance);
    if(balance > 0)
    {
        rightVolume = volumes[volume];
        leftVolume = volumes[(int)floor(volume * ( 1 - (balance * .1)))]];
    }
    else if(balance < 0)
    {
        leftVolume = volumes[volume];
        rightVolume = volumes[(int)floor(volume * ( 1 + (balance * .1)))]];
    }
}

```

```

    }
else
{
    leftVolume = volumes[volume];
    rightVolume = volumes[volume];
}

digitalWrite(CS_PIN, LOW);

SPI.transfer(0x00);
SPI.transfer(leftVolume);

SPI.transfer(0x10);
SPI.transfer(rightVolume);

digitalWrite(CS_PIN, HIGH);

Serial.print("Left Volume: ");
Serial.println(leftVolume);
Serial.print("Right Volume: ");
Serial.println(rightVolume);
}

```

Cost Estimates

Item	Cost(min)	Cost(avg)	Cost(max)	Justification
PCB etching	75.00	100.00	150.00	Around 50 dollars for fabrication and two runs to be safe.
Discrete Passive Components(Resistors, Capacitors, Inductors, etc.)	4.00	5.00	10.00	Usually cost .1 dollars apiece, and 50 over the entire project is a conservative estimate.
Interconnects (Wire, Terminals, Jacks, etc.)	10.00	20.00	30.00	Plugs and jacks cost around 3.00 and this project requires a few.
Filter Components (Large Inductors, Large Capacitors)	15.00	20.00	30.00	Since outputs need to be smooth, large caps and coils are needed which can be 3.00 a piece, and about 6 will be needed.
Output Transistors	5.00	10.00	20.00	These larger transistors cost from 1 dollar to 3 dollars and this project will need several of them.
Enclosure	5.00	20.00	30.00	I can make an enclosure myself inexpensively.
Logic Circuitry (LEDs, OP AMPs, Sensors, etc.)	5.00	10.00	20.00	These are about 1 dollar a piece and about 10 will be needed.
Labor	3200	4800	6400	16 weeks at 10 hrs/week min, 15hrs/week typ, 20hrs/week max. 20.00 dollars per hour.
Total	3,319.00	4,985.00	6,690.00	
Weighted total		4,991.50		Using cost = (min + max + 4 * avg)/ 6

Table 14: Cost Estimates

Gantt Chart

	EE4 60											EE4 63										EE4 64								
W11Task Name	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W1	W2	W3	W4	W5	W6	W7
Define ProblemW9W10																														
Design Approach																														
Implementation																														
Design																														
Build																														
Test																														
Acquire Parts																														
Select																														
Purchase																														
Ship Parts																														
Documentation																														
ABET Sr.																														
Project Analysis																														

Table 15: Proposed senior project design process.

Parts List

Name	Manufacturer	Vendor	Part No	Quantity	Unit Price	Extended Price
50mohm 1206 resistor	Vishay/Dale	Mouser	WSLP1206R0500FEB	1	0.88	0.88
562ohm 1206 resistor	Vishay/Dale	Mouser	CRCW1206-562-E3	1	0.1	0.1
56.2kohm 1206 resistor	Vishay/Dale	Mouser	CRCW120656K2FKEA	1	0.1	0.1
180kohm 1206 resistor	Vishay/Dale	Mouser	CRCW1206180KFKEA	1	0.1	0.1
13kohm 1206 resistor	Vishay/Dale	Mouser	CRCW120613K0FKEA	1	0.1	0.1
18.2kohm 1206 resistor	Vishay/Dale	Mouser	CRCW120618K2FKEA	1	0.1	0.1
10uF ceramic capacitor	Yageo	Mouser	CC1206KKX5R8BB106	3	0.13	0.39
100uF 250V filter capacitor	Panasonic	Mouser	EEU-ED2E101	1	1.82	1.82
3300uF electrolytic capacitor	Panasonic	Mouser	EEU-FR1E332	1	1.78	1.78
100nF 1206 ceramic capacitor	Vishay/Vitramon	Mouser	77-VJ1206Y104KXBMT	3	0.1	0.3
4.7nF ceramic capacitor	Vishay/Vitramon	Mouser	VJ1206Y472JXAAT	1	0.08	0.08
Rectifier Diode	Fairchild	Mouser	RS2K-E3/52T	1	0.28	0.28
4A schottky diode	Vishay	Mouser	VSSB410S-E3/52T	1	0.5	0.5
schottky diode	NXP Semiconductors	Mouser	BAV74,215	2	0.02	0.04
N-Channel MOSFET	Infineon	Mouser	726-IPD60R2K0C6	1	0.57	0.57
12V linear regulator	ON Semiconductor	Mouser	863-MC7812CDTG	1	0.6	0.6
SMPS Transformer	Cooper	Mouser	704-VPH3-0084-R	1	7.15	7.15
2 position terminal block	Pheonix Contact	Mouser	651-1935161	1	0.36	0.36
3 position terminal block	Pheonix Contact	Mouser	651-1935174	1	0.52	0.52
½ Amp Time Delay Fuse	Littelfuse	Mouser	576-0209.500MXEP	1	0.58	0.58
LTC3803 PWM Controller	Linear Technology	Digikey	LTC3803HS6#TRMPBFCT-ND	1	3.75	3.75

Table 16: Flyback Converter Partslist

Name	Manufacturer	Vendor	Part No.	Quantity	Unit Price	Extended Price
1000uF electrolytic capacitor	Nichicon	Mouser	UFW1V102MHD	8	0.69	5.52
470uF electrolytic Capacitor	Nichicon	Mouser	647-UFW1V471MPD	4	0.41	1.64
1uF 1206 ceramic capacitor	Vishay/Vitramon	Mouser	77-VJ1206V105MXATBC	24	0.06	1.44
.1uF 1206 ceramic capacitor	Vishay/Vitramon	Mouser	77-VJ1206Y104KXBMT	12	0.1	1.2
.22uF 1206 ceramic capacitor	Vishay/Vitramon	Mouser	77-VJ1206Y224KXXAC	8	0.17	1.36
.68uF 1206 ceramic capacitor	Vishay/Vitramon	Mouser	810-C3216X7R1H684K	8	0.42	3.36
10uF ceramic capacitor	Yageo	Mouser	81-GRM31CR6YA106KA2L	4	0.37	1.48
22uH SMD inductor	Murata	Mouser	652-SRN6045-220M	8	0.33	2.64
Class D amplifier	Texas Instruments	Mouser	TPA3125D2	4	2.32	9.28
4 Position Terminal Block	Pheonix Contact	Mouser	651-1935187	4	0.64	2.56

Table 17: Amplifier parts list

Name	Manufacturer	Vendor	Part No	Quantity	Unit Price	Extended Price
Adruino Uno	Arduino	Mouser	782-A000049	1	26.95	26.95
Graphical LCD Display	Electronic Assembly	Mouser	EA DOGM128W-6	1	18	18
Rotary Encoder	Bourns	Mouser	652-PEC16-2215FS0024	1	1.53	1.53
Digital Potentiometer	Microchip Techonology	Mouser	MCP4251-503E/P	1	1.02	1.02
XLR 1/4" Combo Jack	Neutrik	Mouser	568-NCJ6FA-V	2	1.89	3.78
RCA Jack Red	Kobiconn	Mouser	161-0370-E	1	0.53	0.53
RCA Jack White	Kobiconn	Mouser	161-0360-E	1	0.53	0.53
4 Pole Speakon Connector	Neutrik	Mouser	568-NL4MDV	2	3.38	6.76
PowerCon Connector	Neutrik	Mouser	568-NAC3MPA-1	1	3.7	3.7
.187" Female Disconnect	Kobiconn	Mouser	159-1641	3	0.1	0.3
6 pole 2 position rotary switch	Alpha	Mouser	105-SR2511F-62FN	1	2.77	2.77
Black D-shaft knob	Eagle Plastic Devices	Mouser	450-BA600	1	0.6	0.6
Black D-shaft knob	Eagle Plastic Devices	Mouser	450-BA761	1	0.34	0.34
knob cap	Eagle Plastic Devices	Mouser	450-CP185	1	0.28	0.28
DPST switch	Cherry Electrical	Mouser	RRA32H3FBBNN	1	1.45	1.45

Table 18: Display Parts List

Name	Manufacturer	Vendor	Part No	Quantity	Unit Price	Extended Price
TL074 Quad Op Amp	ST Microelectronics	Mouser	TL074CN	10	0.52	5.2
10Kohm Resistor	Vishay/Dale	Mouser	71-CRCW1206-10k-E3	25	0.05	1.25
100Kohm Resistor	Vishay/Dale	Mouser	71-CRCW1206-100k-E3	25	0.05	1.25
10uf Capacitor	Vishay/Vitramon	Mouser	603-CC206KKX5R8BB106	8	0.13	1.04
100nF 1206 ceramic capacitor	Vishay/Vitramon	Mouser	77-VJ1206Y104KXBMT	4	0.1	0.4
150pf ceramic capacitor	Vishay/Vitramon	Mouser	CC1206JRNPO0BN151	4	0.09	0.36

Table 19: Balanced/Unbalanced converter parts list

Total Cost: 128.62

Schematics

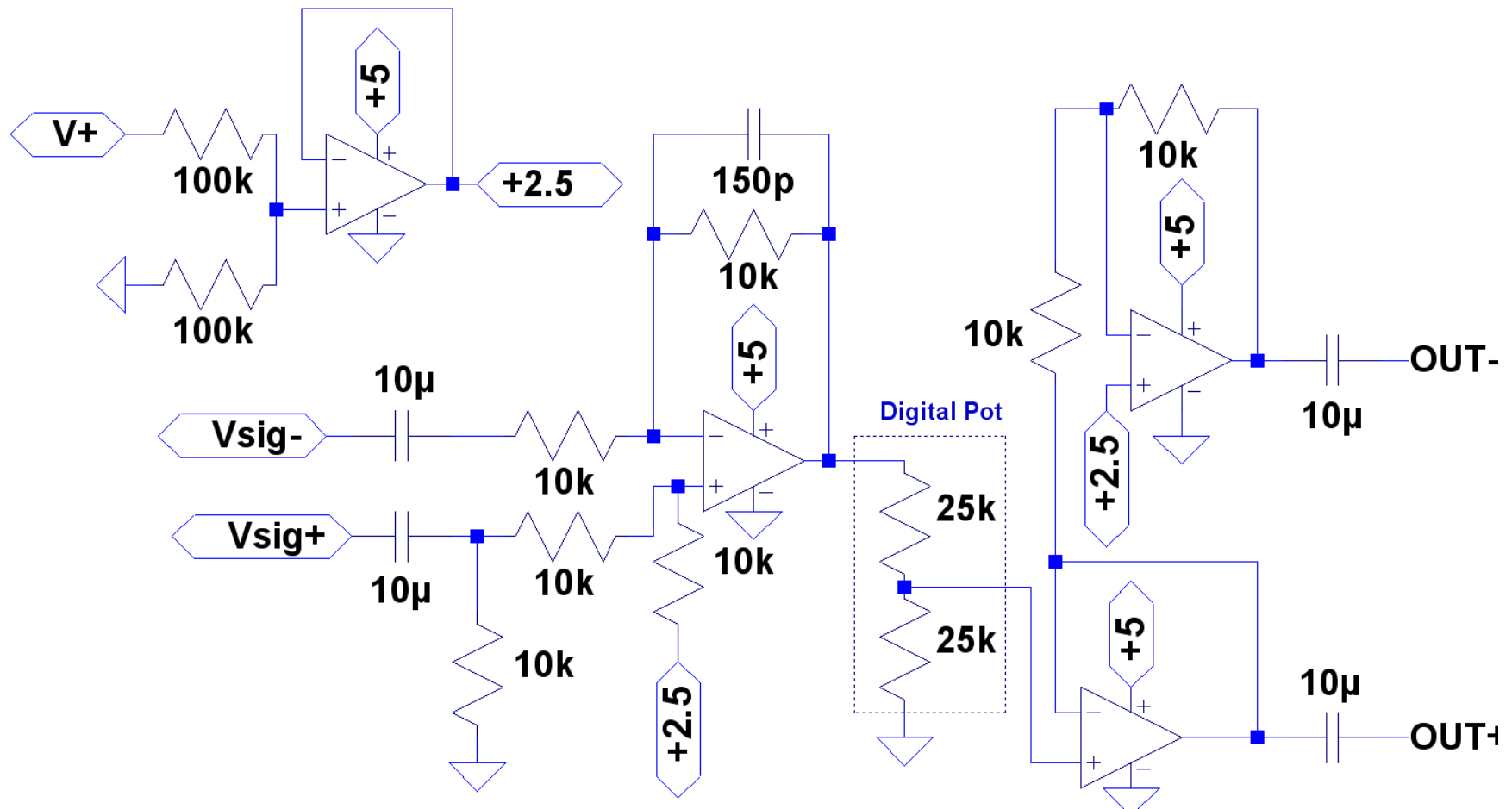
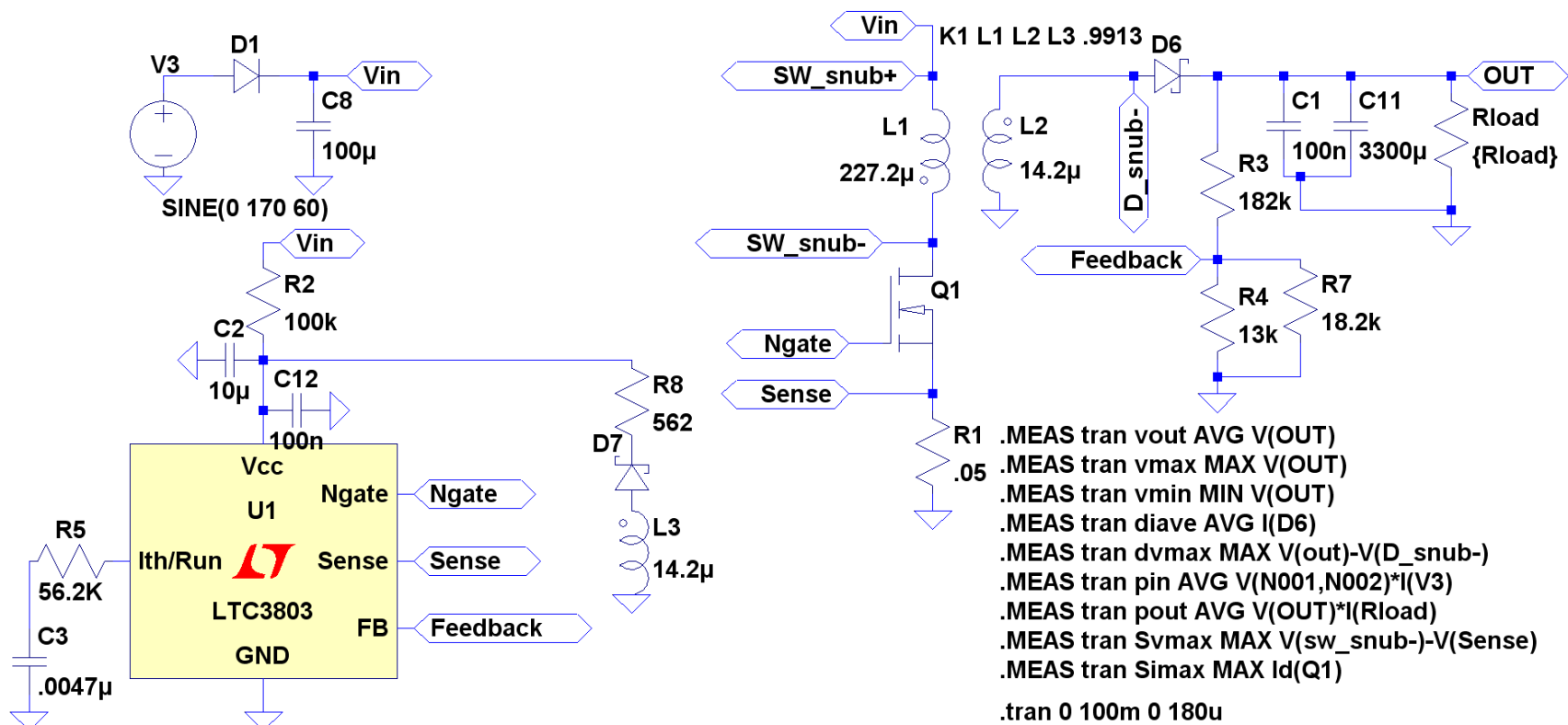


Figure 65: Final schematic of balanced to unbalanced converter. (Only one of two channels shown)



.STEP PARAM Rload list 266.67 133.33 88.89 66.67 53.33 44.44 38.1 33.33 29.63 26.67 24.24 22.22 20.51 19.05 17.78 16.67 15.69 14.81 14.04 13.33

Figure 66: Final Schematic of the flyback converter

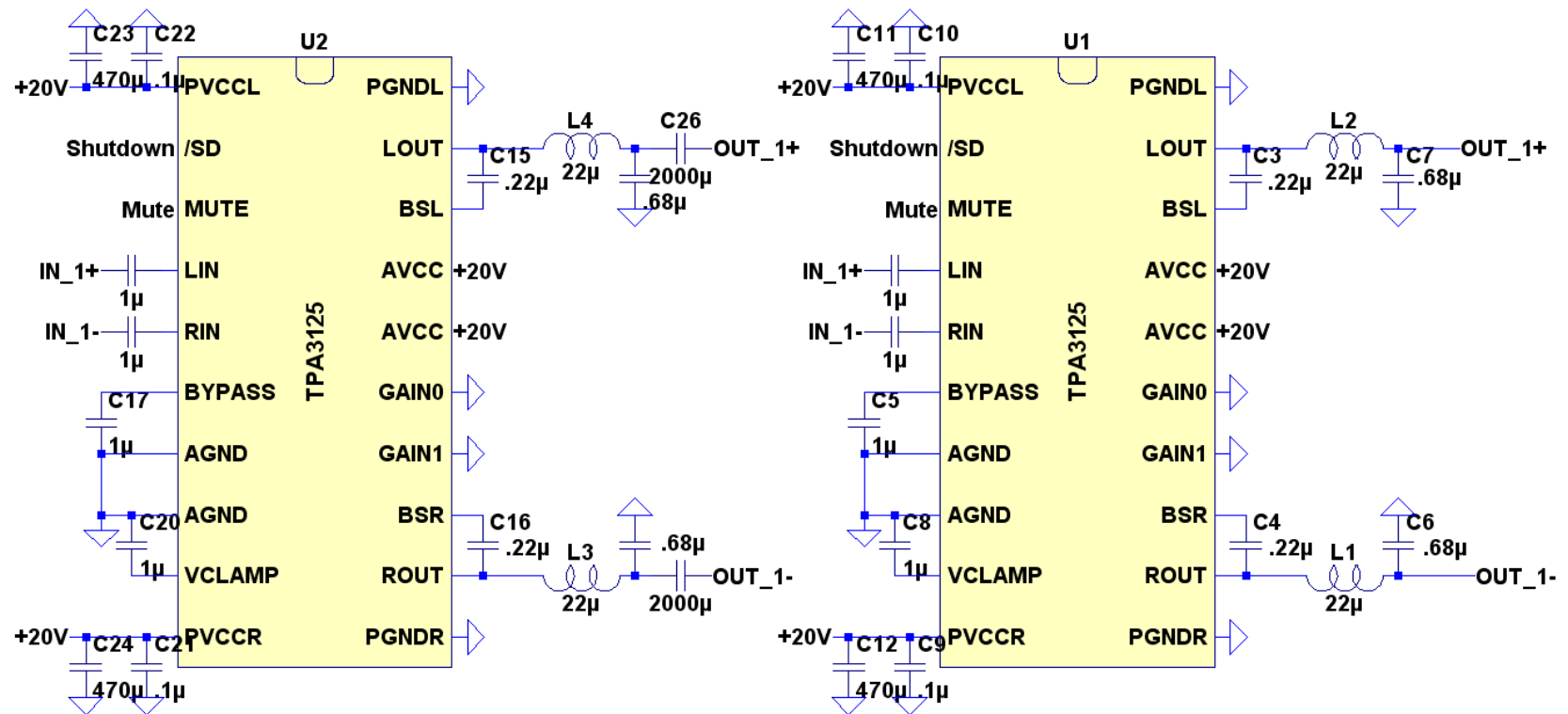


Figure 67: Final Schematic of amplifier (only one of two channels shown)

Artwork

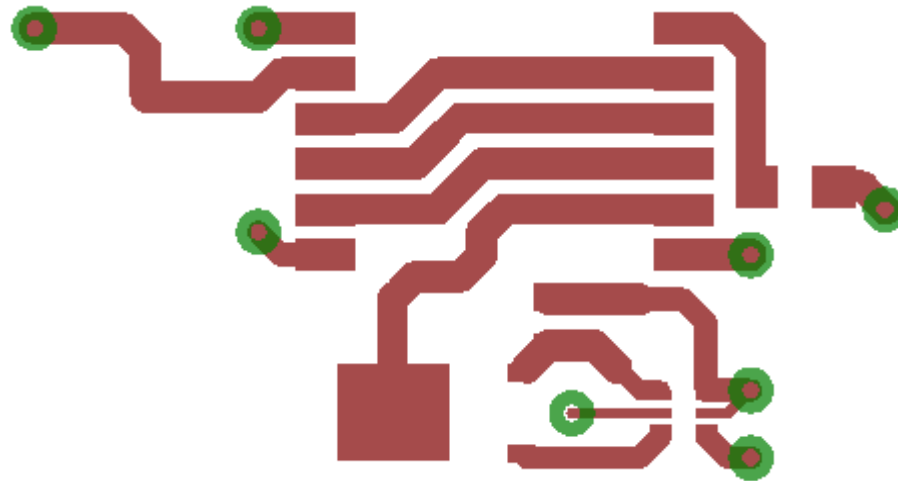


Figure 68: Flyback top layer artwork

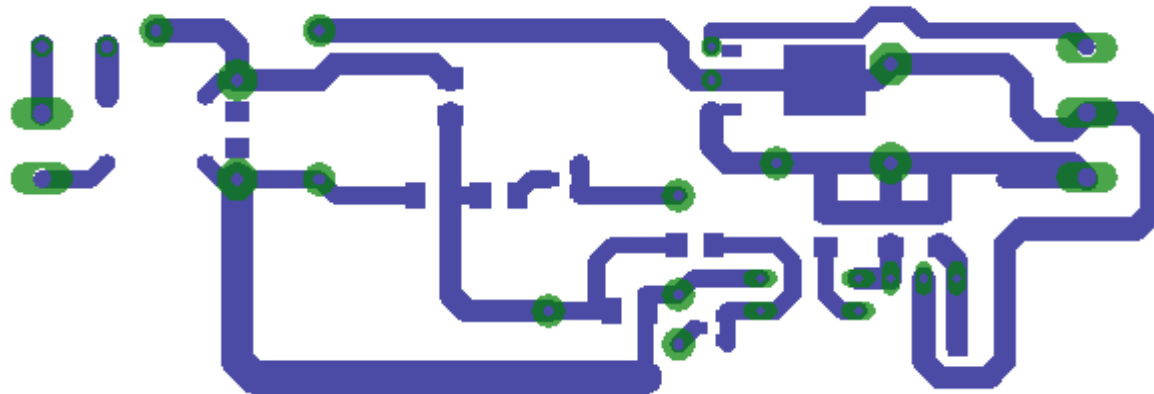


Figure 69: Flyback bottom layer artwork

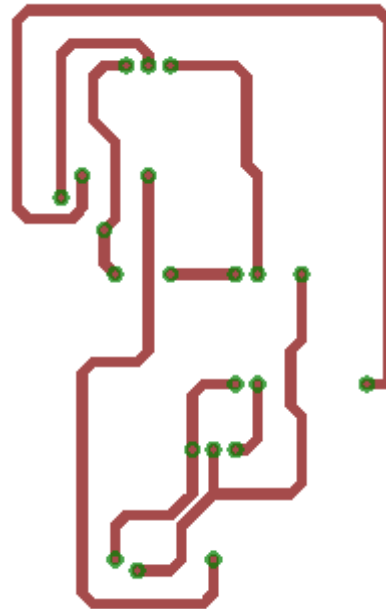


Figure 70:
Balanced/Unbalanced
converter top layer artwork

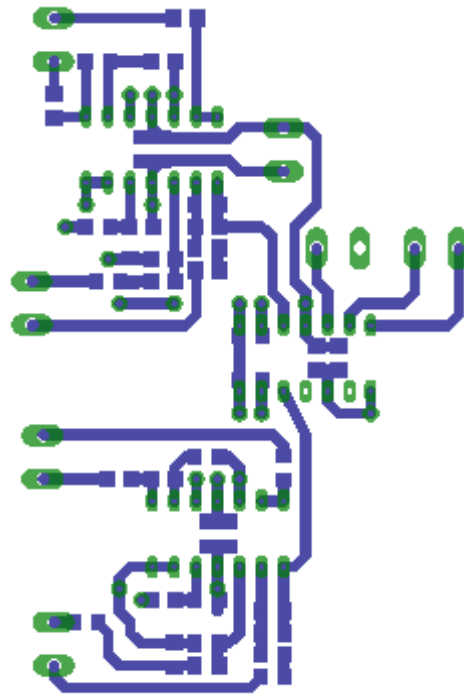


Figure 71: Balanced/Unbalanced converter bottom layer artwork

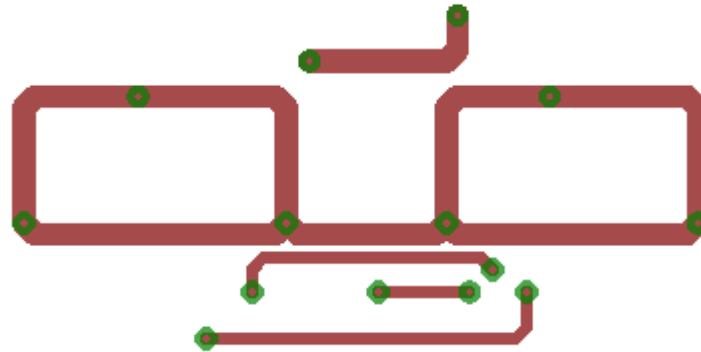


Figure 72: Amplifier top layer artwork

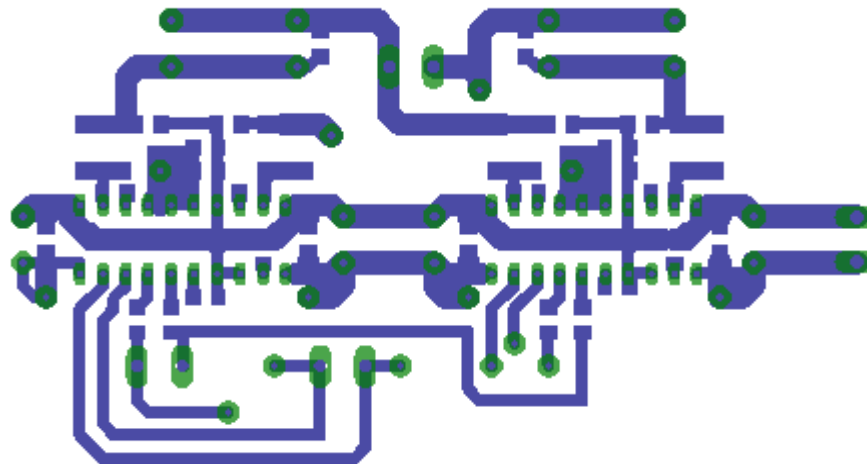


Figure 73: Amplifier bottom layer artwork